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HEAT TRANSFER IN A COMPACT TUBULAR HEAT EXCHANGER WITH HELIUM GAS AT 3.5 MPa

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Nomenclature

A = inlet manifold location

A_f = flow normal area = $n\pi D_h^2/4$

A_n = specimen normal area = $L \cdot W$

A_w = wetted wall area (total wall area exposed to fluid) = $n\pi D_h \cdot L$

B = outlet manifold location

c_p = specific heat at constant pressure

D_h = specimen hydraulic diameter = tube inner diameter

f = friction factor

$f_{heating}$ = friction factor of an experiment with heat transfer

$f_{no.heat}$ = friction factor of an experiment without heat transfer

f_q = heat flux distribution function

G = mass flow rate per unit flow normal area = $\dot{m}/A_f = \rho V$

h = heat transfer coefficient

h = enthalpy

k = thermal conductivity

K = pressure loss coefficient

L = heated length of specimen

$\dot{m}$ = mass flow rate

n = number of tubes

Nu = Nusselt number = $h \cdot D_h/k$

Nu_m = modified Nusselt number = $Nu \cdot (T_w/T_f)^{0.55}$

P = pressure

Pr = Prandtl number = $\mu \cdot c_p/k$

Q_m = heat leak to manifolds through insulation

$Q_{m,in}$ = heat leak to inlet manifold

Q_{px} = fraction of total heat flow on specimen added up to position x
 = integration of furnace calibration function f_q, 0 to x

Q_T = total heat transfer to specimen

q_w = local heat flux (heat flow per unit area) into the cooling fluid based on total wetted-wall area of the specimen

r = recovery factor = $Pr^{1/3}$ for turbulent flow

Re = Reynolds number = $\rho V D_h/\mu$

Re_m = modified Reynolds number = $(\rho_f V_f D_h)/\mu_f \cdot (\nu_f/\nu_m)$

T = temperature

T_{aw} = cooling fluid adiabatic wall temperature

T_f = local bulk fluid temperature

T_m = mean fluid temperature = $(T_f+T_w)/2$

T_w = specimen wall temperature

V = velocity

V_f = heater voltage

W = width of specimen

W_{dh} = uncertainty in inner tube diameter

W_f = uncertainty in friction factor

W_{fu} = uncertainty in tube-to-tube flow uniformity

W_h = uncertainty in heat transfer coefficient

W_K = uncertainty in pressure loss coefficient

W_L = uncertainty in heated length of specimen

W_{loc} = uncertainty in location of wall temperature probe

W_{nu} = uncertainty in Nusselt number

W_{qt} = uncertainty in total heat transfer

Wre = uncertainty in Reynolds number
W_{tf} = uncertainty in fluid temperature
W_{tw} = uncertainty in wall temperature
W_v = uncertainty in fluid velocity
x   = position coordinate parallel to flow direction
y   = position coordinate perpendicular to flow direction

β = coefficient of thermal expansion
μ = dynamic viscosity
ν = kinematic viscosity
ρ = density

0   = location where heating begins (x/L=0)
1   = location where heating ends (x/L=1)

Heat Transfer in a Compact Tubular Heat Exchanger
With Helium Gas at 3.5 MPa

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We have constructed a compact heat exchanger consisting of circular tubes in parallel brazed to a grooved base plate. This tube specimen heat exchanger was tested in an apparatus which radiatively heated the specimen on one side at a heat flux of up to 54 W/cm^2, and cooled the specimen with helium gas at 3.5 MPa and Reynolds numbers of 3000 to 35 000. The measured friction factor of the tube specimen was lower than that of a circular tube with fully developed turbulent flow, although our uncertainty was high due to entrance and exit losses. The measured Nusselt number, when modified to account for differences in fluid properties between the wall and the cooling fluid, agreed with past correlations for fully developed turbulent flow in circular tubes.

Key words: apparatus; compact heat exchanger; circular tube; convection heat transfer; friction factor; high temperature; National Aerospace Plane; radiative furnace; turbulent flow; variable property effects.

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1. Introduction

Development of a National Aerospace Plane (NASP), which will fly at hypersonic speeds, requires novel cooling techniques to manage the anticipated high heat fluxes on various components (Shore, 1986). The problem that motivates this work is cooling of the engine struts. Due to aerodynamic heating associated with the combustion of the hydrogen fuel, along with thermal radiation from the fuel combustion, the engine struts are expected to receive a normal heating load in excess of 2000 W/cm^2 (Scotti et al., 1988). NASA plans to cool the struts by attaching a cooling jacket heat exchanger to the surface facing the high heat flux. Hydrogen gas will flow through the cooling jacket and absorb the heat before entering the engine. The anticipated conditions are that the hydrogen gas will enter the heat exchangers at 56 K and 6.9 MPa (1000 psi), and exit at 890 K and 4.8 MPa (700 psi). The heat exchangers are expected to be thin (6 mm or less) perpendicular to the flow direction to add minimal weight and thickness to the struts. Small flow passages will also produce high rates of convective heat transfer, which will reduce the exchanger temperatures. Reynolds numbers are expected to be in the range 10 000 to 30 000, with the variation due to the flow rate and the specific design of the flow passage.

In order to test heat exchangers developed by NASA, we have constructed an apparatus which can provide helium gas flow and a well-characterized heat flux to a heat exchanger specimen. We have previously described this helium flow loop apparatus (Olson, 1989) and predicted its operating conditions. In this work we have constructed a candidate cooling jacket, which is a tubular heat exchanger specimen. The length and width of the specimen, flow manifold connections, and instrumentation were identical to those of the specimens to be constructed by NASA. We have measured the heat transfer and the friction factor of the tube specimen in the helium flow loop, testing the operating capabilities of the apparatus. We chose the tube geometry because it has been studied extensively (e.g., Ede, 1961, Kays and Leung, 1962), and there are correlations for fully developed turbulent flow in circular tubes which we can compare to our results. We note that these correlations were developed for conditions of much lower heat flux, and for geometries which allowed better access to wall and fluid temperatures, than for our specimen.

2. Description of experimental apparatus

The apparatus was designed to test a subset of the conditions required for the NASP application. Those conditions are (1) a heating rate of 0-80 W/cm^2; (2) an inlet temperature of 300 K; (3) a cooling-gas pressure of up to 6.9 MPa at the inlet; and (4) an outlet temperature of 810 K or less. We chose helium as the coolant gas because of the similarities in specific heat, thermal conductivity, and dynamic viscosity to the corresponding properties of hydrogen. In addition, helium does not have the explosive hazard of hydrogen. Because of the property similarities, the Reynolds number, Prandtl number, and temperature rise from specimen inlet to outlet can be matched between helium and hydrogen.

2.1. Flow loop

The helium flow loop is shown in figure 1, with the details of the specimen furnace section in figure 2. This description is based on Olson (1989). Helium gas at 13.8 MPa (2000 psi) or less was supplied from a tube trailer outside the laboratory. The tube trailer contained 1100 m^3 of gas (STP). With valves 1 and 2 open, gas flowed from the trailer, through the inlet piping, and was filtered before entering the dome-loaded pressure regulator (valve 3). The regulator set the flow pressure downstream of the regulator to the value of an external control pressure, which was 3.5 MPa (500 psi) for the experiments described here.

Within the furnace (fig. 2), the gas flowed into an inlet distribution manifold which directed it to the heat exchanger specimen. A similar distribution manifold collected the gas exiting the specimen and directed it to the outlet tubing. Gas pressure was measured at the pressure taps as shown in the inlet and outlet manifold. The specimen was located in the target area of the furnace (7.8 cm wide by 15.2 cm long), which delivered radiant heat to the specimen and raised the temperature of the helium as it flowed through the specimen.

The furnace consisted of a high-intensity infrared radiant heater, surrounded by refractory insulation, 5 cm thick or greater. The insulation directed and re-radiated the heat from the heater to the specimen. The heater contained six high-temperature infrared lamps mounted in an aluminum housing. A phase-angle power controller which used 480 VAC, single phase, and 75 A at maximum voltage powered the heater. We estimated that the refractory wall temperature would be 2033 K (3200 °F) at 100% power.

Downstream of the furnace section, the hot gas flowed through a cooling coil immersed in a water bath. The rate of gas flow was manually adjusted at the bath outlet by valve 4, which also dropped the gas pressure to atmospheric pressure. Beyond the valve, we measured helium flow rate with a heated-tube thermal mass flow meter. After exiting the flow meter the gas was vented outside the laboratory.

2.2. Tube Specimen

The tube specimen consisted of 20 small-diameter tubes lying in parallel on a base plate as shown in figure 3. The gas was directed into the tubes by the inlet manifold, flowed down the tubes, and was collected in the outlet manifold. Both the tubes and the base plate were made of commercially pure nickel (UNS 02200). The tubes had an outer diameter of 2.0 mm and an inner diameter of 1.0 mm. Adjacent tubes were 3.8 mm on-center, leaving 1.8 mm of flat between the tubes. The base plate was 7.82 cm wide, 16.5 cm long and 3.2 mm thick. The total thickness of the tubes and base plate was 4.2 mm.

The tubes (19 cm long) were brazed to the base plate using a braze alloy foil containing 70% gold, 8% palladium, and 22% nickel (AMS-4786, 1310 K liquidus). The protruding tubes on each end of the base plate were slipped into two header pieces, which were 12.7 mm long by 4.8 mm thick and 7.82 cm wide with holes drilled to match the 20 tubes. The header pieces were brazed

to the tubes and base plate using an alloy of 82% gold and 18% nickel (AMS-4787, 1223 K liquidus). The assembled tube specimen was welded to slots in the inlet and outlet manifolds. Welding the specimen into the manifolds caused some bowing of the specimen due to the thermal stresses of the welding. We pressurized the manifold and specimen to 6.9 MPa (1000 psi) prior to installing the instrumentation, and there were no leaks. We painted the top side of the specimen (with the protruding tube ridges) a flat black over the 15.2 cm length, to establish a uniform and highly absorptive surface over the heated area. The paint was rated to 1000 K (1350 °F).

2.3. Instrumentation

We measured the temperature of the gas in the inlet and outlet manifolds, gas pressure in the manifolds, specimen temperatures, and the aforementioned gas flow rate. The measurement technique and uncertainties, along with the gas property uncertainties, are summarized in table 1.

We determined the distribution of heat flux on the specimen by calibrating the furnace prior to inserting the specimen. The heat flux distribution was defined as the local, normal (perpendicular) heat flux as a function of position over the furnace target and as a function of heater lamp voltage. The heat flux was constant in the direction perpendicular to flow (y), and varied by no more than ±15% in the direction parallel to flow (x). Details of the furnace calibration are given in Olson (1989).

We measured the gas inlet and outlet temperatures with platinum resistance thermometers (PRTs), 4.8 mm diameter, inserted in the gas manifolds at locations A and B of figure 2. We measured the gas pressure in the inlet manifold (location A in fig. 2) with a variable-reluctance pressure transducer which had a 8.6 MPa full scale output. Difference in pressure between the specimen inlet and outlet manifolds (A to B) was measured with a differential pressure transducer, also a variable-reluctance type with a 1.4 MPa full scale output.

We measured specimen temperatures with thermocouples made from type-N wire, with a wire diameter of 0.25 mm. We spot-welded 25 thermocouples to the side opposite the radiant heat flux (insulated-side). The heated-side temperature was measured at 8 locations with type-N thermocouples mounted as shown in figure 4. Two holes, 0.33 mm diameter, were drilled 1.0 mm on-center in the flat between the tube ridges. The holes were back-drilled to within 0.13 mm of the surface with a 0.57 mm diameter drill. We spot-welded each wire of the pair to the heated surface, with the lead extending out the hole on the insulated side. The thermocouple circuit was completed by the specimen material between the two wires. A quartz sleeve, 0.48 mm outer diameter, was inserted over the wire into the hole to electrically insulate the wire from the wall of the hole. Because a portion of the specimen was removed and replaced by wire plus quartz, each of which had a thermal conductivity lower than that of the specimen, mounting the thermocouple locally increased the specimen temperature. We estimated the magnitude of this temperature rise from a finite-element analysis as 2-5 K at a radiant heat flux of 50 W/cm^2. Temperatures measured with the insulated-side thermocouples were used to determine the heat transfer coefficient, as the installation technique did not

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disturb the specimen temperatures.

All thermocouples were connected to an isothermal reference box. We measured the temperature of the reference box with a platinum resistance thermometer. Copper conductor wire connected the reference box to the data scanner. The connector box introduced negligible error in the temperature measurement (Olson, 1989).

All instrument signals were multiplexed through an automated scanner and measured with a digital voltmeter. The scanner and voltmeter were controlled with a personal computer through an IEEE 488 bus. Raw signals were stored on a hard disk and copied to floppy disk for backup. Signals were converted to SI units and the data analyzed at the completion of an experimental run. Some signal readings were converted immediately to SI units and displayed on the video terminal to assist in monitoring and operating the experiment. We have included the measurement uncertainties introduced by the data acquisition system in the stated uncertainties of each sensor.

3. Description of experiments and analysis techniques

3.1 Experiments conducted

A summary of the conditions for the five experiments conducted with the tube specimen in the helium flow loop is shown in table 2. Also listed are the values for the geometrical parameters required for the data analysis. Table 3 lists values for all the measured and calculated parameters at each data point for each experiment. All tests were conducted at approximately 3.5 MPa (500 psi) system pressure. In the first experiment, we tested a range of helium flow rates without heating the specimen to determine the friction factor. Subsequent tests used heater voltages of 7.4%, 20%, 35%, and 61% of maximum with a helium flow rate of up to 40 kg/h; the heater voltage established the heat flux level to the specimen. The range in Reynolds number was 3000 to 35 000, while the range in normal heat flux was 0 to 54 W/cm^2 (48 Btu/(s·ft^2)). The minimum inlet gas temperature was 277 K (39 °F), while the maximum gas outlet temperature was 647 K (705 °F). The maximum specimen temperature was 743 K (877 °F).

Because of the high heat fluxes incident to the tube specimen, we carefully followed a procedure to prevent overheating the specimen during experimental set-up, run, and shut-down. With inadequate helium flow to cool the specimen, the furnace is capable of heating the specimen beyond the melting point of the brazing alloy and the nickel; with an internal pressure of 3.5 MPa this could easily rupture the specimen. We always started helium flow before turning on the furnace, and we maintained helium flow after the furnace was turned off. To set an experimental point, we closed valves 1 and 2, set the control pressure on valve 3, and cracked open valve 4 (see fig. 2). We opened valve 1, and verified that the tube trailer pressure was at least 5.5 MPa (800 psi). Then, we slowly opened valve 2 to full open to establish the helium flow. Valve 4 was adjusted to set a flow rate of at least 5 kg/h. Next, we turned on the furnace heater lamp to a low voltage (10%) while monitoring temperatures. The lamp was then turned up to the desired setting, and the helium flow was increased if necessary to provide sufficient cooling.

Before taking the first data point, we waited at least 15 minutes with the heater lamp at steady power to allow the furnace to reach thermal equilibrium. We scanned the sensors at least twice at each setting. After sampling all the sensors, we changed the helium flow rate by adjusting valve 4. At each new flow rate, we waited about 5 minutes to establish thermal equilibrium before taking data, since a change of flow rate also affected gas and specimen temperatures. After we finished taking data at one heater setting, we turned off the heater and reduced the helium flow to 5 kg/h or less. We turned off the helium flow when the furnace had cooled sufficiently, usually after about 30 minutes.

An unsteady experimental setting could translate into errors in the calculated performance parameters. In the data analysis to follow, we have assumed the settings were sufficiently steady to ignore thermal transients. A steady setting was established by maintaining constant helium flow, gas pressure, furnace heating, and gas inlet temperature. Furnace heating, helium flow, and gas pressure were all held steady to within the uncertainty in the calibrations of the measurements. The gas inlet temperature varied by the largest amount, due to gas expansion in the helium trailer as the trailer pressure decreased. The gas inlet temperature dropped by as much as 0.36 K/min, never dropping lower than 277 K. However, the error this introduced in both the heat delivered to the specimen and the specimen-to-gas temperature difference was less than the calibration uncertainty of the sensors.

For the experiments conducted, we analyzed the measured data to determine the heat transfer coefficient, h, and the friction factor, f. The heat transfer coefficient was non-dimensionalized as a Nusselt number, Nu, which was correlated with the Reynolds number, Re. The parameters h, Re, and Nu were calculated at each location of an insulated-side thermocouple.

3.2. Friction factor

The friction factor results from an integration of the one-dimensional momentum equation in the flow direction:

$$P_0 - P_1 = G^2(1/\rho_1 - 1/\rho_0) + (2G^2/D_h)\int_0^1 (f/\rho)\,dx, \tag{1}$$

where P = pressure;
   G = mass flow rate per unit flow normal area
      = $\dot{m}/A_f = \rho V$;
   A_f = flow normal area = $n \cdot \pi D_h^2/4$;
   ρ = density;
   V = velocity;
   D_h = tube inner diameter;
   n = number of tubes;
   0 = location where heating begins $(x/L = 0)$;
   1 = location where heating ends $(x/L = 1)$.

The first term on the right hand side of the equation is the pressure change due to flow acceleration, and the second term is the pressure drop due to

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frictional effects. We measured pressure in the inlet and outlet manifolds rather than at 0 and 1, so we estimated and subtracted the entry and exit losses for the manifold-to-tube junction. Or,

$$P_0-P_1 = P_A-P_B - \sum_i K_i \rho V^2/2, \tag{2}$$

where the K values for the entrance and exit were estimated based on the local geometry, and V is the entrance or exit velocity (Rohsenow and Hartnett, 1973).

If the density change is small compared to the absolute density, and the pressure drop through the specimen is linear, then the integral can be approximated as a constant and the resulting equation for f is:

$$f = \frac{P_0-P_1 - G^2(1/\rho_1-1/\rho_0)}{2(G^2/\rho)\cdot(L/D_h)}, \tag{3}$$

with $\rho = (\rho_0 + \rho_1)/2$.

The density change criterion was met when there was no heating, but when the specimen was heated the exit density was as small as half the entrance density and eq (3) was not valid.

The friction factor was calculated for experiment 1 where flow rate was varied with no heating. This was equivalent to finding the variation of f with Re, where the Re is defined as

$$Re = \rho V D_h/\mu. \tag{4}$$

3.3. Heat transfer coefficient

The heat transfer coefficient, h, is defined through the equation

$$q_w = h\cdot(T_w-T_{aw}), \tag{5}$$

where q_w = local heat flux (heat flow per unit area) into the cooling fluid based on total wetted-wall area of the specimen;
   h = heat transfer coefficient;
   T_w = specimen wall temperature;
   T_{aw} = adiabatic wall temperature of the cooling fluid.

The adiabatic wall temperature is used in gas flows whenever the kinetic energy is significant compared to enthalpy changes (Rohsenow and Choi, 1961). Friction can cause the local wall temperature to exceed the bulk fluid temperature for an adiabatic specimen, and the adiabatic wall temperature approximates this effect. It is defined as

$$T_{aw} = T_f + rV^2/(2c_p), \tag{6}$$

where T_f = local bulk fluid temperature;
   r = recovery factor = $Pr^{1/3}$ for turbulent flow.

Adiabatic heating was as much as 2 K for the highest flow rate and heating rate tested. The local heat flux in eq (5) is expressed in terms of the total heat transfer to the specimen, Q_T, the total wetted wall area, and the furnace calibration function, f_q (Olson, 1989), which is a dimensionless expression of the local normal heat flux:

$$q_w = (Q_T/A_n) \cdot f_q \cdot (A_n/A_w), \tag{7}$$

with A_w = wetted wall area = $n \cdot \pi D_h \cdot L$;
A_n = specimen heated normal area = $L \cdot W$.

The function f_q is on the order of 1, and if the heat flux were constant then f_q is 1 everywhere. The wall temperature used in eq (5) was measured with the thermocouples on the insulated side of the specimen. We have assumed that wall conduction was negligible in the flow direction, and thus at each position the heat incident on the specimen is all convected into the fluid.

In the defining equation of h we assume (1) that the heat flux into the cooling fluid is uniform at a particular x location (the same at all circumferential points around a tube), (2) that the wall temperature is uniform around the tube, and (3) that the insulated side temperature is the same as the wall temperature at the tube/fluid interface. Because the specimen was heated from one side only and heat flowed through the specimen structure to enter the fluid from the lower portions of the tube, wall temperatures were not constant. However, since the Biot number (ratio of wall conduction resistance to fluid convection resistance) was less than 1, temperature variations in the specimen should be much less than the temperature difference between the wall and the fluid. A finite-element conduction analysis using anticipated values of the heat transfer coefficient indicated that the tube wall temperature varied from 1.2 K greater than to 3.8 K less than the insulated side temperature (for 50 W/cm^2 hot side heat flux and h = 11 200 W/(m$^2 \cdot$K)). This compares with a temperature difference between the wall and bulk fluid of at least 54 K for the same conditions.

Combining eqs (5), (6) and (7) and rearranging, we get

$$h = \frac{(Q_T/A_w) \cdot f_q}{\{T_w - [T_f + (rV^2)/(2c_p)]\}}. \tag{8}$$

The flow-direction energy equation was used to calculate Q_T (to follow). Gas temperature T_f was calculated using the flow-direction energy equation along with the furnace calibration (also to follow).

The total heat absorbed by the tube specimen equals the total heat absorbed by the specimen plus manifolds, minus the heat leak through the furnace insulation into the manifolds, Q_m. It was calculated from the temperatures of the gas inlet and outlet, the gas pressure drop, and an estimation of the manifold heat leak. Or

$$Q_T = \dot{m} \cdot (h_B - h_A) - Q_m, \tag{9}$$

where h = enthalpy;

A = location in inlet manifold of PRT;
B = location in outlet manifold of PRT;
Q_m = heat leak to manifolds through insulation.

Heat absorbed by the manifold was typically 2-5% of the total heat flow, which we measured during a calibration on the furnace before inserting the test specimen. We neglected kinetic energy changes from A to B since they were insignificant compared to the uncertainties of the temperature measurement. The change in enthalpy is given by

$$h_B - h_A = c_p \cdot (T_B - T_A) + \int_A^B [(1 - \beta T)/\rho] \, dP, \tag{10}$$

where β = coefficient of thermal expansion.

The pressure term was significant because helium is not an ideal gas at these temperatures and pressures. The integral was evaluated using the virial equation of state for the gas (McCarty, 1973). Combining eqs (9) and (10) yield for Q_T:

$$Q_T = \dot{m}\{c_p \cdot (T_B - T_A) + \int_A^B [(1 - \beta T)/\rho] \, dP\} - Q_m. \tag{11}$$

The fluid temperature, T_f, was calculated by integrating the flow energy equation from the inlet manifold up to the location of interest (designated as x), now including kinetic energy:

$$T_{fx} = T_A + \frac{Q_T \cdot Q_{px}}{\dot{m} c_p} + \frac{Q_{m,in}}{\dot{m} c_p} - \frac{\int_A^x [(1 - \beta T)/\rho] \, dP}{c_p} - \frac{V_x^2}{2 c_p}, \tag{12}$$

where Q_{px} = fraction of total heat flow on specimen added up to
          position x;
      = integration of furnace calibration function f_q, 0 to x;
$Q_{m,in}$ = heat leak to inlet manifold.

We assume in eq (12) that the helium flow has split evenly into all 20 of the tubes. The fluid temperature requires the velocity at x, given by

$$V_x = \dot{m}/(A_f \rho_x), \tag{13}$$

and the density is given by the equation of state (McCarty, 1973) as

$$\rho_x = \rho_x(T_{fx}, P_x). \tag{14}$$

We assume the pressure varies linearly between 0 and 1:

$$P_x = P_0 - (P_0 - P_1) \cdot x/L. \tag{15}$$

The maximum error in T_f introduced by our assumption of a linear pressure variation is less than 0.02 K.

With eq (15) substituted into eq (12) to evaluate the pressure term, eqs (12), (13), and (14) form a system of three equations in the unknowns of temperature, velocity, and density. They were solved through iteration.

With T_f and V determined at location x, the heat transfer coefficient was calculated using eq (8). The Nusselt number, Prandtl number, and Reynolds number were then calculated, with the transport properties evaluated at the bulk fluid temperature, T_f:

$$Nu = h \cdot D_H/k,$$
$$Pr = \mu \cdot c_p/k. \tag{16}$$

Transport properties were calculated from the functions given in McCarty (1972). The Nu, Pr, and Re performance parameters assume constant fluid properties at the location x. Due to the large wall-to-fluid temperature difference, viscosity and thermal conductivity varied between the wall and the fluid (variation was greater than 20% for the lowest helium flow at 61% heater voltage). We used the temperature ratio method of Rohsenow and Hartnett (1973) to correlate the data by calculating:

$$Nu_m = Nu \cdot (T_w/T_f)^{0.55}. \tag{17}$$

3.4 Uncertainty analysis

Uncertainties for the calculated quantities were obtained by Taylor series error propagation as described by ASME (1986). This technique generally produces the same level of confidence in a calculated result as the level of confidence in the measurements which contribute to the result (Kline and McClintock, 1953). A summary of the uncertainties in the data analysis parameters and in the calculated quantities is listed in table 4. Actual values at the experimental points are included in table 3. The largest contributor to the uncertainties in T_f, h, and Nu was the flow distribution uncertainty (i.e., whether or not the flow had split evenly into the 20 tubes), particularly near the exit of the tubes. Unfortunately, there was no way to confirm that the flow was evenly split, and the listed uncertainty is based on transverse temperature measurements in the specimen, which would be constant if the flow were evenly distributed.

4. Results of experiments

4.1 Friction factor

Experiment 1 (no heating) was conducted to determine the variation of the friction factor with Reynolds number (eq 3). Figure 5 shows the variation in f with Re along with a least-squares correlation of the data (for Re > 5000) and the Karman-Nikuradse relation for fully developed turbulent flow in a smooth tube (Rohsenow and Hartnett, 1973). Our data are correlated with:

$$f = 0.07532 \cdot Re^{-0.2693}. \tag{18}$$

The standard deviation of the difference between the measured and correlated

values is 2.78%. The points for Re < 5000 were not included in the correlation because the flow was either laminar or transitional.

The measured values were about 18-20% lower than those given by the accepted smooth tube correlation. Our estimate of the uncertainty in the measured friction factor was 12-14%, except for the point at Re = 2200, where the uncertainty was 37.5% due to the large relative uncertainty of the pressure measurement. For Re > 5000, the entrance and exit losses were estimated as 22-32% of the pressure drop from point 0 to 1, and the uncertainties in the losses are the dominant component of the uncertainty in f. These losses must be subtracted from the pressure drop measured with the transducer (eq 2). To estimate the uncertainty, we have assumed the loss coefficients have an uncertainty of 0.2 (they can vary from 0 to 1 depending on the geometry). If the losses were zero, then the measured friction factor would be about 10% higher than the accepted values. Since we could not measure the internal flow geometries of the manifolds and entrance/exit sections after assembly, we may have over-estimated the losses.

We used the friction factor correlation developed for the tests without heat transfer to predict the pressure drop when the specimen was heated. For experiments 2 to 5, the Reynolds number decreased from the inlet to the outlet because the temperature increased. We estimated the pressure drop by calculating f at each location of a measured wall temperature (from eq 18); then, we used eq (1) in a summation form and added up the total pressure drop from 0 to 1. We compared this pressure drop to the measured pressure drop minus the entrance/exit losses (eq 2). Figure 6 compares the predicted-to-measured pressure drop for experiments 3 to 5, plotted against the ratio of wall temperature to gas temperature (taken at $x/L = 0.5$ and $y/W = 0$). No heating corresponds to $T_w/T_f = 1$. This variable was used because it measures the effect of variable properties in the fluid; to first order, k, ρ, and μ all vary most strongly with temperature. As the temperature ratio increases, the differences between the values of the properties at the tube wall and those in the mixed core increases. The error in the predicted temperature increased as the temperature ratio increased (the measured pressure drop was less than the predicted pressure drop), although most points fell within the ±14% uncertainty band of the friction factor. The trend in the data agrees with the findings of Rohsenow and Choi (1961), and Rohsenow and Hartnett (1973), who report that for $T_w/T_f > 1$ (heating) the friction factor decreases. We attempted to correct for the gas heating through the method of Rohsenow and Choi. In this method, the equation for f is taken to be

$$f_{heating} = (T_f/T_m) \cdot f_{no.heat}, \tag{19}$$

$$\text{with } T_m = (T_w + T_f)/2,$$

and the $f_{no.heat}$ is found from eq (18) using a modified Reynolds number:

$$Re_m = (\rho_f V_f D_h)/\mu_f \cdot (\nu_f/\nu_m) . \tag{20}$$

Figure 7 shows the result. This correlation condenses the error in the predicted pressure drop a few percent (the maximum difference decreased from 22% to 17%), but does not change the trend. We made no further attempt at

correlating the effect of the variable properties since the uncertainty in the friction factor was on the same order as the error in the predicted pressure drop.

4.2 Temperature distributions and heat transfer

Experiments 2 to 5 determined the heat transfer performance of the tube specimen. A typical plot of temperatures in the helium gas and along the tube is shown in figure 8. The data are from experiment 5 at the lowest flowrate tested, which corresponded to the largest inlet-to-outlet temperature rise. The measured specimen temperatures along the y centerline (y/W = 0), both for the insulated side and the heated side, are shown from the inlet to the outlet. The calculated gas temperature is also plotted (eq 12) for the locations of an insulated-side thermocouple. The gas temperature increased approximately linearly from the inlet to the outlet. The rate of increase was slightly less near the entrance and exit, due to the drop-off in the heat flux near the furnace end-walls (see Olson 1989). The heated-side temperatures were slightly higher than the insulated-side temperatures, which was expected since the heat impinged directly on that side of the specimen. Temperatures on both sides increased steadily from the inlet to the outlet, except that the temperature decreased near the outlet.

Because the temperature increased from the inlet to the outlet, other fluid properties changed significantly also. Both thermal conductivity and dynamic viscosity increase with temperature, so they increased from the inlet to the outlet. Fluid density decreased from the inlet to the outlet, due primarily to the temperature increase but also to the pressure drop. Because density decreased, fluid velocity increased from the inlet to the outlet; for the conditions shown in the figure, the specimen inlet velocity was 40 m/s and the specimen outlet velocity was 83 m/s.

Temperatures at locations perpendicular to the flow direction (y-variation) for the conditions of figure 8 are shown in figure 9. Here, at each x-location we have plotted temperature on the insulated side as a function of y-position. Only at x/L = 0.5 were the probes positioned entirely across the specimen. Temperatures were fairly constant over the middle of the specimen, although they decreased slightly from the negative to positive y positions. The trace at x/L = 0 showed the most variability. Since this was the location where shading ended and heating began, uncertainty in the shading boundary produces the largest uncertainty in heat flux and therefore in temperature. The temperature at x/L = 0.5 and y/W = -0.46 was 50 K higher than the temperature at x/L = 0.5 and y/W = 0.0. We believe maldistribution of flow (flow in some of the tubes greater or less than that in the others) was the most likely cause of these variations in temperature. Non-uniform heat flux distribution in the y direction could also cause these temperature variations, but we checked the heat flux calibration after running the tests and found no variation in y direction heat flux beyond experimental uncertainty.

A maldistribution of flow could cause a temperature variation in the following manner. If the flow in a tube were less than the average, the fluid would heat up more than expected as it flowed down the tube. Also, the

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lower fluid velocity would produce a smaller heat transfer coefficient, and the wall-to-fluid temperature difference would have to be greater to accommodate the heat flux. These two effects would cause higher wall temperatures for regions with flow lower than average; similarly, regions with flow higher than average would have lower wall temperatures. We have assumed a 5% variation from uniform flow in the uncertainty analysis; this produces uncertainties in T_f, V, Re, h, and Nu. The uncertainties in T_f, h, and Nu grow with distance down the tube. For figure 9, the 5% uncertainty in uniform flow distribution explains all the variations in wall temperature except for the point at $x/L = 0.5$ and $y/W = -0.46$, where an 18% flow maldistribution is required to explain the wall temperature.

The temperature at the hot side probe at $x = 7.595$ cm and $y = -3.048$ cm was likely in error, although it has been included in the data tables. Successive temperature readings at the same conditions of flow and heat flux showed it to vary by 100 K or more. We suspected an intermittent short as the cause.

In figure 10 we show the heat transfer coefficient and wall-to-fluid temperature difference for the same conditions as those for figure 8 (experiment 5, 12.8 kg/h helium flow). Shown are points along $y/W = 0$, again from the inlet to the outlet. h was calculated directly from the temperature difference, with the appropriate heat flux (eq 8); to first order the trends in T_w-T_f and h are mirrored. The temperature difference was relatively flat in the center portion of the specimen, dropping off dramatically near the furnace end walls ($x/L = 0$ and 1). A 15% decrease near the inlet/outlet was expected due to the heat flux distribution, but the measured decrease was much greater. We believe the cause of the drop-off was heat conduction through the specimen wall to the inlet and outlet manifolds. The temperatures of the manifolds were the same as the inlet/outlet gas temperatures, which were lower than the specimen wall temperature at $x/L = 0$ and 1. We estimated the effect of wall conduction using a 1-dimensional model of the specimen as a "fin" (Rohsenow and Choi, 1961) assuming: (1) constant heat flux from $0 \leq x/L \leq 1$ with zero heat flux for $x/L < 0$ and $x/L > 1$; (2) constant fluid temperature for $x/L < 0$, increasing linearly from $0 \leq x/L \leq 1$, and constant for $x/L > 1$; and (3) constant heat transfer coefficient. The results showed that in the initial 20% and final 20% of the heated zone for this specimen, wall temperatures were significantly influenced by conduction to the manifolds. In these regions, h and therefore Nu cannot be calculated from eq (8), since the heat convected into the fluid was not the same as that incident on the specimen.

Figure 11 shows the variation of Re and Nu with x for the same experimental conditions of above. We have plotted Nu along the entire heated length, although because of conduction effects the values are accurate only for $0.2 < x/L < 0.8$. The Reynolds number decreased from the inlet to the outlet, due to the increase in viscosity caused by the temperature increase. Nu also decreased from the inlet to the outlet, within the $0.2 < x/L < 0.8$ region of accuracy.

The trends in temperature distributions, Re, and Nu with position did not change qualitatively for the other helium flow rates for experiment 5, nor did

they change for the other heat flux rates tested. Figures 8 to 11 are representative of the variations for all runs.

Figure 12 shows the modified Nusselt number plotted against the Reynolds number for all experiments for data points at $y/W = 0$ and $0.2 < x/L < 0.8$. Also plotted are three correlations from the literature given for fully developed turbulent flow in circular tubes. The difference between the correlations gives some idea of the uncertainty in using an individual correlation. Those correlations are:

Dittus-Boelter: $\quad\quad\quad\quad\quad\quad\quad\quad$ $Nu = 0.023 \cdot Re^{0.8} \cdot Pr^{0.4}$,
(in Rohsenow and Choi, 1961)

Rohsenow and Hartnett (1973): $\quad$ $Nu = 0.022 \cdot Re^{0.8} \cdot Pr^{0.6}$,

Kays and Leung (1962): $\quad\quad\quad$ $Nu = 0.0422 \cdot Re^{0.74} \cdot Pr^{0.56}$. $\quad\quad$ (21)

The correlation of Kays and Leung is a curve-fit of their theoretical analysis over the range $0.5 < Pr < 0.7$ and $10^4 < Re < 3 \times 10^4$. The data scatter of past investigators about the correlation curve is often $\pm 30\%$ (e.g., see Ede, 1961). We have shown the correlation for our data for $Re > 10\ 000$, which is the fully turbulent region. This is:

$$Nu_m = 0.0420 \cdot Re^{0.739} \cdot Pr^{0.6}, \quad\quad\quad\quad (22)$$

or in terms of Nu,

$$Nu = 0.0420 \cdot Re^{0.739} \cdot Pr^{0.6} \cdot (T_w/T_f)^{-0.55}. \quad\quad (23)$$

The standard deviation between our data and correlation is 1.5% ($Re > 10\ 000$). We have assumed a 0.6 power variation on Pr, and the leading coefficient was calculated based on that variation. The Prandtl number was 0.665 for all experiments. The Reynolds number power and the leading coefficient were calculated from a least-squares fit.

Our data agreed very well with the past correlations, when we accounted for the effect of variable properties in the temperature ratio as suggested by Rohsenow and Hartnett (1973). The temperature ratio for these experiments varied from 1.06 to 1.41, producing a difference between Nu and Nu_m of 3% to 21% (Nu_m being higher). Without accounting for the effect of variable properties in the temperature ratio, our data fell below the accepted correlations by 20% at the highest temperature ratio. Also, plots of Nu vs Re for different heat flux rates would not collapse onto a single curve. The uncertainty in the measured Nu and Nu_m was 6.6% to 13.0%; the lower uncertainties occurred closer to the inlet, and the higher uncertainties occurred closer to the outlet (due to the contribution from the uncertainty in flow distribution).

5. Conclusions

We have constructed a thin, compact heat exchanger specimen consisting of circular tubes in parallel brazed to a grooved base plate. The heat exchanger was made of commercially pure nickel. This tube specimen was tested in an

apparatus which radiatively heated one side of the specimen at a heat flux of up to 54 W/cm^2 (48 Btu/(s·ft^2)), and cooled the specimen with helium gas at 3.5 MPa (500 psi) and Re of 3000 to 35 000. Helium gas temperatures ranged from 277 K (39 °F) to 647 K (705 °F); the peak specimen temperature was 743 K (877 °F). The apparatus was designed to test candidate cooling jackets for the engine struts of the National Aerospace Plane. Measurements showed the friction factor of the tube specimen was lower than that of a circular tube with fully developed turbulent flow, although the uncertainties in our measurements was high due to estimations of entrance and exit losses. Variable property effects appeared to be important in the friction factor. The measured Nusselt number, when modified to account for the effects of variable properties, agreed with past correlations for fully developed turbulent flow in circular tubes. At these temperatures and pressures, there were no unusual effects due to using helium as a heat transfer fluid. Conduction to the end manifolds was important in the first 20% and last 20% of the heated portion of the specimen.

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6. References

ASME, 1986, "ASME Performance Test Codes Supplement on Instruments and Apparatus - Part 1 - Measurement Uncertainty," ANSI/ASME PTC 19.1-1985.

Ede, A. J., 1961, "The Heat Transfer Coefficient for Flow in a Pipe," Int. J. of Heat Mass Transfer, Vol. 4, pp. 105-110.

Kays, W. M., and Leung, E. Y., 1962, "Heat Transfer in Annular Passages - Hydrodynamically Developed Turbulent Flow with Arbitrarily Prescribed Heat Flux," Int. J. of Heat Mass Transfer, Vol. 6, pp. 537-557.

Kline, S. J., and McClintock, F. A., 1953, "Describing Uncertainties in Single-Sample Experiments," Mechanical Engineering, Vol. 75, pp. 3-8.

McCarty, R. D., 1972, "Thermophysical Properties of Helium-4 from 2 to 1500 K with Pressures to 1000 Atmospheres," NBS-TN-631.

McCarty, R. D., 1973, "Thermodynamic Properties of Helium 4 from 2 to 1500 K at Pressures to 10^8 Pa," J. Phys. Chem. Ref. Data, Vol. 2, no. 4, pp. 923-1042.

Olson, D. A., 1989, "Apparatus for Measuring High-Flux Heat Transfer in Radiatively Heated Compact Exchangers," NISTIR 89-3926.

Rohsenow, W. M., and Choi, H., 1961, Heat, Mass, and Momentum Transfer, Prentice-Hall, Inc., Englewood Cliffs.

Rohsenow, W. M., and Hartnett, J. P., 1973, Handbook of Heat Transfer, McGraw-Hill, Inc., New York.

Scotti, S. J., Martin, C. J., and Lucas, S. H., 1988, "Active Cooling Design for Scramjet Engines Using Optimization Methods," NASA TM-100581.

Shore, C. P., 1986, "Review of Convectively Cooled Structures for Hypersonic Flight," NASA TM-87740.

Table 1. Uncertainties in experimental measurements and gas properties at a 95% confidence interval

Measurement/Property	Technique	Major Source of Uncertainty	Magnitude of Uncertainty
Gas Flow Rate	Thermal Mass Flow Meter	Meter Calibration	±1%
Heat Flux	Calibration of Furnace	Heat Flow Meter	±4%
Gas Inlet and Outlet Temperatures	Platinum Resistance Thermometer	Radiation	±0.5 K
Gas Pressure	Pressure Transducer	Calibration	±0.25% of reading
Gas Differential Pressure	Pressure Transducer	Calibration	greater of ±0.5% of reading or ±300 Pa
Specimen Temperature	Type-N Thermocouple	Wire Calibration, Installation	greater of ±0.4% of $T(°C)$ or ±1.1 K
Gas Density	Thermodynamic Function	Function Accuracy	±0.1%
Gas Enthalpy	Thermodynamic Function	Function Accuracy	±0.2%
Gas Specific Heat	Thermodynamic Function	Function Accuracy	±5%
Gas Viscosity	Thermodynamic Function	Function Accuracy	±10%
Gas Thermal Conductivity	Thermodynamic Function	Function Accuracy	±3%

Table 2. Summary of geometrical parameters and experimental conditions
for tube specimen

Number of Tubes, $n = 20$

Tube Inner Diameter, $D_h = 1.016$ mm

Specimen Heated Length, $L = 15.24$ cm

Specimen Width, $W = 7.82$ cm

Specimen Heated Normal Area, $A_n = 119.2$ cm^2

Specimen Wetted Wall Area, $A_w = 97.3$ cm^2

Flow Normal Area, $A_f = 0.1621$ cm^2

Expt. #	Date	Inlet Pressure (kPa)	Heater Voltage (%)	Normal Heat Flux (W/m^2)	Helium Flow Rate (kg/h)	Reynolds Number
1	2/8/90	3400	0.0	0.0	2.6-40.1	2200-36 000
2	2/13/90	3500	7.4	3.4	5.7	4500-5000
3	3/9/90	3550	20.0	16.1	5.3-39.0	3000-35 000
4	2/16/90	3500	35.0	31.3	8.6-38.8	4700-35 000
5	3/9/90	3550	60.8	53.7	12.8-38.3	6600-34 000

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Table 3. Data tables for all experiments

Tube Specimen
Date: 8 February 1990
Time: 15:41:00

TA	TB	M	PA	PA-PB	Vf	f	Wf
K	K	kg/h	kPa	kPa	%		%
302.51	301.85	2.56	3375.0	1.3	0.00	0.00759	37.48

Hot-side Temperatures:

X	Y	Tw
cm	cm	K
1.270	-0.762	302.11
2.515	-0.762	302.12
5.080	-0.381	302.09
7.620	-0.381	302.11
10.185	-0.381	302.10
12.700	-0.381	302.09
13.970	-0.381	302.07
7.595	-3.048	302.15

Insulated-Side Temperatures and Calculated Data:

								--Uncertainties--		
X	Y	Tw	Tf	P	V	RE	PR	Wtw	Wtf	Wre
cm	cm	K	K	kPa	m/s			K	K	%
-0.020	0.191	302.14	302.50	3374.8	8.31	2214	0.665	1.10	0.50	11.58
1.288	0.191	302.16	302.44	3374.7	8.30	2214	0.665	1.10	0.50	11.58
2.586	0.140	302.14	302.39	3374.6	8.30	2214	0.665	1.10	0.50	11.58
3.810	0.165	302.16	302.33	3374.5	8.30	2214	0.665	1.10	0.50	11.58
5.042	0.191	302.16	302.28	3374.5	8.30	2215	0.665	1.10	0.50	11.58
6.350	0.203	302.14	302.23	3374.4	8.30	2215	0.665	1.10	0.50	11.58
7.620	0.191	302.13	302.17	3374.3	8.30	2215	0.665	1.10	0.50	11.58
8.903	0.152	302.14	302.11	3374.3	8.30	2215	0.665	1.10	0.50	11.58
10.160	0.216	302.13	302.06	3374.2	8.29	2216	0.665	1.10	0.50	11.58
11.430	0.191	302.12	302.01	3374.1	8.29	2216	0.665	1.10	0.50	11.58
12.637	0.140	302.10	301.95	3374.1	8.29	2216	0.665	1.10	0.50	11.58
13.912	0.165	302.08	301.90	3374.0	8.29	2217	0.665	1.10	0.50	11.58
15.240	0.165	301.98	301.84	3373.9	8.29	2217	0.665	1.10	0.50	11.58
-0.036	2.083	302.02	302.50	3374.8	8.31	2214	0.665	1.10	0.50	11.58
2.510	2.108	302.07	302.39	3374.6	8.30	2214	0.665	1.10	0.50	11.58
5.105	2.070	302.08	302.28	3374.5	8.30	2215	0.665	1.10	0.50	11.58
7.650	2.096	302.05	302.17	3374.3	8.30	2215	0.665	1.10	0.50	11.58
10.190	2.121	302.08	302.06	3374.2	8.29	2216	0.665	1.10	0.50	11.58
12.700	2.096	302.03	301.95	3374.1	8.29	2216	0.665	1.10	0.50	11.58
15.215	2.070	301.91	301.84	3373.9	8.29	2217	0.665	1.10	0.50	11.58
0.000	-2.070	302.20	302.50	3374.8	8.31	2214	0.665	1.10	0.50	11.58
7.620	-2.146	302.21	302.17	3374.3	8.30	2215	0.665	1.10	0.50	11.58
15.240	-2.096	302.06	301.84	3373.9	8.29	2217	0.665	1.10	0.50	11.58
7.620	3.620	302.11	302.17	3374.3	8.30	2215	0.665	1.10	0.50	11.58
7.620	-3.620	302.18	302.17	3374.3	8.30	2215	0.665	1.10	0.50	11.58

Table 3 (continued)

Tube Specimen
Date: 8 February 1990
Time: 15:46:12

TA	TB	M	PA	PA-PB	Vf	f	Wf
K	K	kg/h	kPa	kPa	%		%
300.77	301.36	5.42	3372.5	6.1	-0.01	0.00773	12.74

Hot-side Temperatures:

X	Y	Tw
cm	cm	K
1.270	-0.762	300.67
2.515	-0.762	300.73
5.080	-0.381	300.76
7.620	-0.381	300.79
10.185	-0.381	300.83
12.700	-0.381	300.84
13.970	-0.381	300.88
7.595	-3.048	300.77

Insulated-Side Temperatures and Calculated Data:

								--Uncertainties--		
X	Y	Tw	Tf	P	V	RE	PR	Wtw	Wtf	Wre
cm	cm	K	K	kPa	m/s			K	K	%
-0.020	0.191	300.74	300.74	3371.6	17.49	4701	0.665	1.10	0.50	11.58
1.288	0.191	300.70	300.79	3371.2	17.49	4701	0.665	1.10	0.50	11.58
2.586	0.140	300.72	300.84	3370.9	17.49	4700	0.665	1.10	0.50	11.58
3.810	0.165	300.71	300.89	3370.6	17.50	4700	0.665	1.10	0.50	11.58
5.042	0.191	300.74	300.93	3370.3	17.50	4699	0.665	1.10	0.50	11.58
6.350	0.203	300.72	300.98	3370.0	17.51	4699	0.665	1.10	0.50	11.58
7.620	0.191	300.73	301.03	3369.7	17.51	4698	0.665	1.10	0.50	11.58
8.903	0.152	300.71	301.08	3369.4	17.52	4698	0.665	1.10	0.50	11.58
10.160	0.216	300.74	301.13	3369.0	17.52	4697	0.665	1.10	0.50	11.58
11.430	0.191	300.74	301.18	3368.7	17.52	4697	0.665	1.10	0.50	11.58
12.637	0.140	300.73	301.23	3368.4	17.53	4696	0.665	1.10	0.50	11.58
13.912	0.165	300.77	301.28	3368.1	17.53	4696	0.665	1.10	0.50	11.58
15.240	0.165	300.81	301.33	3367.8	17.54	4695	0.665	1.10	0.50	11.58
-0.036	2.083	300.69	300.74	3371.6	17.49	4701	0.665	1.10	0.50	11.58
2.510	2.108	300.64	300.84	3370.9	17.49	4700	0.665	1.10	0.50	11.58
5.105	2.070	300.67	300.94	3370.3	17.50	4699	0.665	1.10	0.50	11.58
7.650	2.096	300.66	301.04	3369.7	17.51	4698	0.665	1.10	0.50	11.58
10.190	2.121	300.69	301.13	3369.0	17.52	4697	0.665	1.10	0.50	11.58
12.700	2.096	300.70	301.23	3368.4	17.53	4696	0.665	1.10	0.50	11.58
15.215	2.070	300.76	301.33	3367.8	17.54	4695	0.665	1.10	0.50	11.58
0.000	-2.070	300.57	300.74	3371.6	17.49	4701	0.665	1.10	0.50	11.58
7.620	-2.146	300.58	301.03	3369.7	17.51	4698	0.665	1.10	0.50	11.58
15.240	-2.096	300.76	301.33	3367.8	17.54	4695	0.665	1.10	0.50	11.58
7.620	3.620	300.67	301.03	3369.7	17.51	4698	0.665	1.10	0.50	11.58
7.620	-3.620	300.57	301.03	3369.7	17.51	4698	0.665	1.10	0.50	11.58

Table 3 (continued)

Tube Specimen
Date: 8 February 1990
Time: 15:51:12

TA	TB	M	PA	PA-PB	Vf	f	Wf
K	K	kg/h	kPa	kPa	%		%
296.40	297.63	10.89	3374.4	20.4	0.00	0.00617	11.66

Hot-side Temperatures:

X	Y	Tw
cm	cm	K
1.270	-0.762	296.36
2.515	-0.762	296.40
5.080	-0.381	296.43
7.620	-0.381	296.46
10.185	-0.381	296.49
12.700	-0.381	296.51
13.970	-0.381	296.53
7.595	-3.048	296.35

Insulated-Side Temperatures and Calculated Data:

								--Uncertainties--		
X	Y	Tw	Tf	P	V	RE	PR	Wtw	Wtf	Wre
cm	cm	K	K	kPa	m/s			K	K	%
-0.020	0.191	296.43	296.29	3371.2	34.61	9536	0.665	1.10	0.50	11.58
1.288	0.191	296.36	296.39	3370.2	34.63	9534	0.665	1.10	0.50	11.58
2.586	0.140	296.37	296.49	3369.2	34.65	9532	0.665	1.10	0.50	11.58
3.810	0.165	296.36	296.59	3368.2	34.67	9530	0.665	1.10	0.50	11.58
5.042	0.191	296.38	296.69	3367.2	34.70	9528	0.665	1.10	0.50	11.58
6.350	0.203	296.37	296.80	3366.2	34.72	9526	0.665	1.10	0.50	11.58
7.620	0.191	296.38	296.90	3365.2	34.74	9523	0.665	1.10	0.50	11.58
8.903	0.152	296.36	297.00	3364.2	34.76	9521	0.665	1.10	0.50	11.58
10.160	0.216	296.35	297.10	3363.2	34.78	9519	0.665	1.10	0.50	11.58
11.430	0.191	296.38	297.21	3362.2	34.81	9517	0.665	1.10	0.50	11.58
12.637	0.140	296.33	297.30	3361.2	34.83	9515	0.665	1.10	0.50	11.58
13.912	0.165	296.36	297.41	3360.2	34.85	9513	0.665	1.10	0.50	11.58
15.240	0.165	296.46	297.51	3359.1	34.87	9511	0.665	1.10	0.50	11.58
-0.036	2.083	296.58	296.29	3371.2	34.61	9536	0.665	1.10	0.50	11.58
2.510	2.108	296.40	296.49	3369.2	34.65	9532	0.665	1.10	0.50	11.58
5.105	2.070	296.37	296.70	3367.2	34.70	9528	0.665	1.10	0.50	11.58
7.650	2.096	296.38	296.90	3365.1	34.74	9523	0.665	1.10	0.50	11.58
10.190	2.121	296.38	297.11	3363.1	34.78	9519	0.665	1.10	0.50	11.58
12.700	2.096	296.38	297.31	3361.2	34.83	9515	0.665	1.10	0.50	11.58
15.215	2.070	296.47	297.51	3359.2	34.87	9511	0.665	1.10	0.50	11.58
0.000	-2.070	296.08	296.29	3371.2	34.61	9536	0.665	1.10	0.50	11.58
7.620	-2.146	296.01	296.90	3365.2	34.74	9523	0.665	1.10	0.50	11.58
15.240	-2.096	296.21	297.51	3359.1	34.87	9511	0.665	1.10	0.50	11.58
7.620	3.620	296.48	296.90	3365.2	34.74	9523	0.665	1.10	0.50	11.58
7.620	-3.620	295.98	296.90	3365.2	34.74	9523	0.665	1.10	0.50	11.58

Table 3 (continued)

Tube Specimen
Date: 8 February 1990
Time: 15:55:03

TA	TB	M	PA	PA-PB	Vf	f	Wf
K	K	kg/h	kPa	kPa	%		%
291.82	292.98	20.03	3373.2	60.4	0.00	0.00520	12.82

Hot-side Temperatures:

X	Y	Tw
cm	cm	K
1.270	-0.762	291.52
2.515	-0.762	291.53
5.080	-0.381	291.55
7.620	-0.381	291.58
10.185	-0.381	291.62
12.700	-0.381	291.63
13.970	-0.381	291.64
7.595	-3.048	291.46

Insulated-Side Temperatures and Calculated Data:

								--Uncertainties--		
X	Y	Tw	Tf	P	V	RE	PR	Wtw	Wtf	Wre
cm	cm	K	K	kPa	m/s			K	K	%
-0.020	0.191	291.53	291.45	3363.4	62.78	17734	0.665	1.10	0.50	11.58
1.288	0.191	291.48	291.55	3360.4	62.86	17730	0.665	1.10	0.50	11.58
2.586	0.140	291.48	291.64	3357.5	62.93	17726	0.665	1.10	0.50	11.58
3.810	0.165	291.46	291.73	3354.8	63.00	17723	0.665	1.10	0.50	11.58
5.042	0.191	291.43	291.82	3352.0	63.07	17719	0.665	1.10	0.50	11.58
6.350	0.203	291.49	291.92	3349.1	63.15	17715	0.665	1.10	0.50	11.58
7.620	0.191	291.44	292.01	3346.2	63.22	17712	0.665	1.10	0.50	11.58
8.903	0.152	291.38	292.11	3343.4	63.29	17708	0.665	1.10	0.50	11.58
10.160	0.216	291.39	292.20	3340.5	63.37	17704	0.665	1.10	0.50	11.58
11.430	0.191	291.38	292.30	3337.7	63.44	17701	0.665	1.10	0.50	11.58
12.637	0.140	291.37	292.38	3335.0	63.51	17697	0.665	1.10	0.50	11.58
13.912	0.165	291.35	292.48	3332.1	63.58	17694	0.665	1.10	0.50	11.58
15.240	0.165	291.40	292.58	3329.2	63.66	17690	0.665	1.10	0.50	11.58
-0.036	2.083	291.73	291.45	3363.4	62.78	17734	0.665	1.10	0.50	11.58
2.510	2.108	291.47	291.64	3357.7	62.93	17727	0.665	1.10	0.50	11.58
5.105	2.070	291.42	291.83	3351.9	63.08	17719	0.665	1.10	0.50	11.58
7.650	2.096	291.43	292.02	3346.2	63.22	17712	0.665	1.10	0.50	11.58
10.190	2.121	291.46	292.20	3340.5	63.37	17704	0.665	1.10	0.50	11.58
12.700	2.096	291.43	292.39	3334.9	63.51	17697	0.665	1.10	0.50	11.58
15.215	2.070	291.54	292.58	3329.2	63.66	17690	0.665	1.10	0.50	11.58
0.000	-2.070	291.11	291.45	3363.3	62.78	17734	0.665	1.10	0.50	11.58
7.620	-2.146	290.98	292.01	3346.2	63.22	17712	0.665	1.10	0.50	11.58
15.240	-2.096	291.07	292.58	3329.2	63.66	17690	0.665	1.10	0.50	11.58
7.620	3.620	291.58	292.01	3346.2	63.22	17712	0.665	1.10	0.50	11.58
7.620	-3.620	290.95	292.01	3346.2	63.22	17712	0.665	1.10	0.50	11.58

Table 3 (continued)

Tube Specimen
Date: 8 February 1990
Time: 15:59:25

TA	TB	M	PA	PA-PB	Vf	f	Wf
K	K	kg/h	kPa	kPa	%		%
285.43	286.29	40.06	3374.3	223.0	0.00	0.00457	14.16

Hot-side Temperatures:

X	Y	Tw
cm	cm	K
1.270	-0.762	284.94
2.515	-0.762	284.96
5.080	-0.381	284.95
7.620	-0.381	284.96
10.185	-0.381	284.96
12.700	-0.381	284.96
13.970	-0.381	284.94
7.595	-3.048	284.90

Insulated-Side Temperatures and Calculated Data:

								--Uncertainties--		
X	Y	Tw	Tf	P	V	RE	PR	Wtw	Wtf	Wre
cm	cm	K	K	kPa	m/s			K	K	%
-0.020	0.191	284.89	283.99	3337.5	123.32	36075	0.664	1.10	0.52	11.58
1.288	0.191	284.86	284.04	3327.0	123.72	36071	0.664	1.10	0.53	11.58
2.586	0.140	284.84	284.10	3316.7	124.13	36067	0.664	1.10	0.53	11.58
3.810	0.165	284.83	284.16	3306.9	124.51	36063	0.664	1.10	0.53	11.58
5.042	0.191	284.83	284.21	3297.1	124.90	36059	0.664	1.10	0.53	11.58
6.350	0.203	284.86	284.27	3286.7	125.31	36055	0.664	1.10	0.53	11.58
7.620	0.191	284.82	284.33	3276.6	125.72	36051	0.664	1.10	0.53	11.58
8.903	0.152	284.74	284.38	3266.3	126.13	36047	0.664	1.10	0.53	11.58
10.160	0.216	284.76	284.44	3256.3	126.54	36043	0.664	1.10	0.53	11.58
11.430	0.191	284.78	284.50	3246.2	126.95	36039	0.664	1.10	0.53	11.58
12.637	0.140	284.73	284.55	3236.5	127.35	36035	0.664	1.10	0.53	11.58
13.912	0.165	284.70	284.61	3226.4	127.77	36031	0.664	1.10	0.53	11.58
15.240	0.165	284.76	284.67	3215.8	128.21	36027	0.664	1.10	0.53	11.58
-0.036	2.083	285.14	283.99	3337.6	123.31	36075	0.664	1.10	0.52	11.58
2.510	2.108	284.79	284.10	3317.3	124.10	36067	0.664	1.10	0.53	11.58
5.105	2.070	284.76	284.21	3296.6	124.92	36059	0.664	1.10	0.53	11.58
7.650	2.096	284.78	284.33	3276.3	125.73	36051	0.664	1.10	0.53	11.58
10.190	2.121	284.76	284.44	3256.1	126.55	36043	0.664	1.10	0.53	11.58
12.700	2.096	284.76	284.55	3236.0	127.37	36035	0.664	1.10	0.53	11.58
15.215	2.070	284.85	284.66	3216.0	128.20	36027	0.664	1.10	0.53	11.58
0.000	-2.070	284.63	283.99	3337.3	123.32	36075	0.664	1.10	0.52	11.58
7.620	-2.146	284.42	284.33	3276.6	125.72	36051	0.664	1.10	0.53	11.58
15.240	-2.096	284.49	284.67	3215.8	128.21	36027	0.664	1.10	0.53	11.58
7.620	3.620	284.93	284.33	3276.6	125.72	36051	0.664	1.10	0.53	11.58
7.620	-3.620	284.43	284.33	3276.6	125.72	36051	0.664	1.10	0.53	11.58

Table 3 (continued)

Tube Specimen
Date: 8 February 1990
Time: 16:02:11

TA	TB	M	PA	PA-PB	Vf	f	Wf
K	K	kg/h	kPa	kPa	%		%
283.77	284.33	31.02	3401.5	134.8	0.00	0.00485	13.50

Hot-side Temperatures:

X	Y	Tw
cm	cm	K
1.270	-0.762	283.70
2.515	-0.762	283.75
5.080	-0.381	283.76
7.620	-0.381	283.78
10.185	-0.381	283.80
12.700	-0.381	283.83
13.970	-0.381	283.85
7.595	-3.048	283.81

Insulated-Side Temperatures and Calculated Data:

								--Uncertainties--		
X	Y	Tw	Tf	P	V	RE	PR	Wtw	Wtf	Wre
cm	cm	K	K	kPa	m/s			K	K	%
-0.020	0.191	283.84	282.93	3379.3	94.00	28007	0.664	1.10	0.51	11.58
1.288	0.191	283.86	282.97	3372.9	94.19	28005	0.664	1.10	0.51	11.58
2.586	0.140	283.84	283.01	3366.5	94.38	28003	0.664	1.10	0.51	11.58
3.810	0.165	283.85	283.05	3360.5	94.56	28000	0.664	1.10	0.51	11.58
5.042	0.191	283.86	283.09	3354.4	94.74	27998	0.664	1.10	0.51	11.58
6.350	0.203	283.88	283.13	3348.0	94.93	27996	0.664	1.10	0.51	11.58
7.620	0.191	283.85	283.17	3341.8	95.12	27994	0.664	1.10	0.51	11.58
8.903	0.152	283.83	283.21	3335.5	95.31	27991	0.664	1.10	0.51	11.58
10.160	0.216	283.87	283.25	3329.3	95.50	27989	0.664	1.10	0.51	11.58
11.430	0.191	283.85	283.29	3323.1	95.69	27987	0.664	1.10	0.51	11.58
12.637	0.140	283.84	283.33	3317.2	95.87	27985	0.664	1.10	0.51	11.58
13.912	0.165	283.87	283.37	3310.9	96.06	27982	0.664	1.10	0.51	11.58
15.240	0.165	283.89	283.42	3304.4	96.26	27980	0.664	1.10	0.51	11.58
-0.036	2.083	284.20	282.93	3379.4	94.00	28007	0.664	1.10	0.51	11.58
2.510	2.108	283.93	283.01	3366.9	94.37	28003	0.664	1.10	0.51	11.58
5.105	2.070	283.94	283.09	3354.1	94.75	27998	0.664	1.10	0.51	11.58
7.650	2.096	283.93	283.17	3341.7	95.12	27994	0.664	1.10	0.51	11.58
10.190	2.121	283.97	283.26	3329.2	95.50	27989	0.664	1.10	0.51	11.58
12.700	2.096	283.98	283.33	3316.9	95.88	27984	0.664	1.10	0.51	11.58
15.215	2.070	284.04	283.41	3304.5	96.25	27980	0.664	1.10	0.51	11.58
0.000	-2.070	283.87	282.93	3379.2	94.00	28007	0.664	1.10	0.51	11.58
7.620	-2.146	283.76	283.17	3341.8	95.12	27994	0.664	1.10	0.51	11.58
15.240	-2.096	283.82	283.42	3304.4	96.26	27980	0.664	1.10	0.51	11.58
7.620	3.620	284.14	283.17	3341.8	95.12	27994	0.664	1.10	0.51	11.58
7.620	-3.620	283.80	283.17	3341.8	95.12	27994	0.664	1.10	0.51	11.58

Table 3 (continued)

Tube Specimen
Date: 8 February 1990
Time: 16:07:01

TA	TB	M	PA	PA-PB	Vf	f	Wf
K	K	kg/h	kPa	kPa	%		%
285.69	285.62	13.88	3436.4	30.5	0.00	0.00596	11.77

Hot-side Temperatures:

X	Y	Tw
cm	cm	K
1.270	-0.762	285.82
2.515	-0.762	285.86
5.080	-0.381	285.91
7.620	-0.381	285.90
10.185	-0.381	285.92
12.700	-0.381	285.97
13.970	-0.381	285.98
7.595	-3.048	285.97

Insulated-Side Temperatures and Calculated Data:

								--Uncertainties--		
X	Y	Tw	Tf	P	V	RE	PR	Wtw	Wtf	Wre
cm	cm	K	K	kPa	m/s			K	K	%
-0.020	0.191	286.00	285.52	3431.6	41.81	12458	0.664	1.10	0.50	11.58
1.288	0.191	286.00	285.51	3430.1	41.83	12458	0.664	1.10	0.50	11.58
2.586	0.140	286.05	285.51	3428.5	41.85	12459	0.664	1.10	0.50	11.58
3.810	0.165	286.05	285.50	3427.1	41.86	12459	0.664	1.10	0.50	11.58
5.042	0.191	286.07	285.50	3425.7	41.88	12459	0.664	1.10	0.50	11.58
6.350	0.203	286.07	285.49	3424.1	41.90	12459	0.664	1.10	0.50	11.58
7.620	0.191	286.08	285.48	3422.6	41.92	12460	0.664	1.10	0.50	11.58
8.903	0.152	286.09	285.48	3421.1	41.93	12460	0.664	1.10	0.50	11.58
10.160	0.216	286.11	285.47	3419.7	41.95	12460	0.664	1.10	0.50	11.58
11.430	0.191	286.12	285.46	3418.2	41.97	12460	0.664	1.10	0.50	11.58
12.637	0.140	286.13	285.46	3416.8	41.98	12460	0.664	1.10	0.50	11.58
13.912	0.165	286.13	285.45	3415.3	42.00	12461	0.664	1.10	0.50	11.58
15.240	0.165	286.12	285.45	3413.7	42.02	12461	0.664	1.10	0.50	11.58
-0.036	2.083	286.24	285.52	3431.6	41.81	12458	0.664	1.10	0.50	11.58
2.510	2.108	286.19	285.51	3428.6	41.85	12459	0.664	1.10	0.50	11.58
5.105	2.070	286.20	285.49	3425.6	41.88	12459	0.664	1.10	0.50	11.58
7.650	2.096	286.19	285.48	3422.6	41.92	12460	0.664	1.10	0.50	11.58
10.190	2.121	286.21	285.47	3419.6	41.95	12460	0.664	1.10	0.50	11.58
12.700	2.096	286.21	285.46	3416.7	41.98	12460	0.664	1.10	0.50	11.58
15.215	2.070	286.19	285.45	3413.7	42.02	12461	0.664	1.10	0.50	11.58
0.000	-2.070	286.25	285.52	3431.6	41.81	12458	0.664	1.10	0.50	11.58
7.620	-2.146	286.26	285.48	3422.6	41.92	12460	0.664	1.10	0.50	11.58
15.240	-2.096	286.23	285.45	3413.7	42.02	12461	0.664	1.10	0.50	11.58
7.620	3.620	286.36	285.48	3422.6	41.92	12460	0.664	1.10	0.50	11.58
7.620	-3.620	286.32	285.48	3422.6	41.92	12460	0.664	1.10	0.50	11.58

Table 3 (continued)

Tube Specimen
Date: 8 February 1990
Time: 16:12:41

TA	TB	M	PA	PA-PB	Vf	f	Wf
K	K	kg/h	kPa	kPa	%		%
289.36	288.43	6.25	3466.4	7.4	0.00	0.00763	11.93

Hot-side Temperatures:

X	Y	Tw
cm	cm	K
1.270	-0.762	289.21
2.515	-0.762	289.23
5.080	-0.381	289.23
7.620	-0.381	289.23
10.185	-0.381	289.24
12.700	-0.381	289.21
13.970	-0.381	289.19
7.595	-3.048	289.38

Insulated-Side Temperatures and Calculated Data:

								--Uncertainties--		
X	Y	Tw	Tf	P	V	RE	PR	Wtw	Wtf	Wre
cm	cm	K	K	kPa	m/s			K	K	%
-0.020	0.191	289.33	289.32	3465.3	18.89	5560	0.664	1.10	0.50	11.58
1.288	0.191	289.35	289.24	3464.9	18.89	5561	0.664	1.10	0.50	11.58
2.586	0.140	289.39	289.17	3464.5	18.88	5562	0.664	1.10	0.50	11.58
3.810	0.165	289.38	289.09	3464.1	18.88	5563	0.664	1.10	0.50	11.58
5.042	0.191	289.40	289.02	3463.7	18.88	5564	0.664	1.10	0.50	11.58
6.350	0.203	289.39	288.94	3463.3	18.88	5565	0.664	1.10	0.50	11.58
7.620	0.191	289.42	288.86	3463.0	18.87	5566	0.664	1.10	0.50	11.58
8.903	0.152	289.44	288.78	3462.6	18.87	5567	0.664	1.10	0.50	11.58
10.160	0.216	289.43	288.70	3462.2	18.87	5568	0.664	1.10	0.50	11.58
11.430	0.191	289.44	288.63	3461.8	18.86	5569	0.664	1.10	0.50	11.58
12.637	0.140	289.43	288.55	3461.4	18.86	5570	0.664	1.10	0.50	11.58
13.912	0.165	289.39	288.48	3461.0	18.86	5571	0.664	1.10	0.50	11.58
15.240	0.165	289.30	288.39	3460.6	18.85	5572	0.664	1.10	0.50	11.58
-0.036	2.083	289.39	289.32	3465.3	18.89	5560	0.664	1.10	0.50	11.58
2.510	2.108	289.44	289.17	3464.5	18.88	5562	0.664	1.10	0.50	11.58
5.105	2.070	289.45	289.01	3463.7	18.88	5564	0.664	1.10	0.50	11.58
7.650	2.096	289.50	288.86	3462.9	18.87	5566	0.664	1.10	0.50	11.58
10.190	2.121	289.48	288.70	3462.2	18.87	5568	0.664	1.10	0.50	11.58
12.700	2.096	289.44	288.55	3461.4	18.86	5570	0.664	1.10	0.50	11.58
15.215	2.070	289.30	288.40	3460.6	18.85	5572	0.664	1.10	0.50	11.58
0.000	-2.070	289.68	289.32	3465.3	18.89	5560	0.664	1.10	0.50	11.58
7.620	-2.146	289.72	288.86	3463.0	18.87	5566	0.664	1.10	0.50	11.58
15.240	-2.096	289.51	288.39	3460.6	18.85	5572	0.664	1.10	0.50	11.58
7.620	3.620	289.56	288.86	3463.0	18.87	5566	0.664	1.10	0.50	11.58
7.620	-3.620	289.80	288.86	3463.0	18.87	5566	0.664	1.10	0.50	11.58

Table 3 (continued)

Tube Specimen
Date: 13 February 1990
Time: 16:03:24

TA	TB	M	PA	PA-PB	Vf	Qt	Wqt
K	K	kg/h	kPa	kPa	%	W	%
291.06	343.16	5.71	3487.6	6.8	7.39	407.0	1.82

Hot-side Temperatures:

X	Y	Tw
cm	cm	K
1.270	-0.762	311.47
2.515	-0.762	317.90
5.080	-0.381	327.64
7.620	-0.381	336.18
10.185	-0.381	344.82
12.700	-0.381	352.27
13.970	-0.381	353.44
7.595	-3.048	320.69

Insulated-Side Temperatures and Calculated Data:

											Uncertainties				
X	Y	Tw	Tf	Taw	P	V	RE	PR	h	NU	Wtw	Wtf	Wre	Wh	Wnu
cm	cm	K	K	K	kPa	m/s			W/(m²·K)		K	K	%	%	%
-0.020	0.191	302.01	292.44	292.47	3486.6	17.34	5046	0.665	0	0.00	1.10	0.51	11.58	13.53	14.00
1.288	0.191	310.83	296.06	296.08	3486.3	17.56	5006	0.665	2681	17.56	1.10	0.60	11.58	9.91	10.54
2.586	0.140	317.45	300.20	300.23	3485.9	17.80	4960	0.665	2459	15.96	1.10	0.70	11.58	8.95	9.65
3.810	0.165	322.46	304.27	304.29	3485.6	18.04	4915	0.665	2380	15.31	1.10	0.84	11.58	8.96	9.66
5.042	0.191	326.73	308.42	308.44	3485.2	18.28	4870	0.665	2387	15.22	1.10	1.02	11.58	9.44	10.10
6.350	0.203	331.27	312.86	312.88	3484.9	18.54	4823	0.665	2390	15.09	1.10	1.23	11.58	10.10	10.73
7.620	0.191	335.57	317.19	317.22	3484.5	18.80	4779	0.665	2400	15.02	1.10	1.44	11.58	10.93	11.51
8.903	0.152	339.82	321.56	321.59	3484.2	19.05	4734	0.665	2411	14.95	1.10	1.62	11.58	11.72	12.26
10.160	0.216	344.13	325.83	325.86	3483.9	19.30	4692	0.665	2387	14.66	1.10	1.81	11.58	12.50	13.01
11.430	0.191	348.45	330.09	330.12	3483.5	19.55	4651	0.665	2349	14.31	1.10	2.01	11.58	13.35	13.83
12.637	0.140	351.58	334.08	334.11	3483.2	19.79	4613	0.665	2406	14.54	1.10	2.20	11.58	14.88	15.31
13.912	0.165	353.01	338.11	338.15	3482.8	20.03	4576	0.665	2645	15.85	1.10	2.40	11.58	18.48	18.83
15.240	0.165	349.55	341.83	341.86	3482.5	20.24	4542	0.665	4128	24.55	1.10	2.58	11.58	37.12	37.29
-0.036	2.083	304.08	292.44	292.47	3486.6	17.34	5046	0.665	0	0.00	1.10	0.51	11.58	11.43	11.98
2.510	2.108	316.25	299.95	299.98	3485.9	17.78	4962	0.665	2597	16.87	1.10	0.69	11.58	9.31	9.98
5.105	2.070	326.24	308.63	308.66	3485.2	18.30	4868	0.665	2484	15.83	1.10	1.03	11.58	9.76	10.40
7.650	2.096	334.94	317.29	317.32	3484.5	18.80	4778	0.665	2500	15.64	1.10	1.45	11.58	11.32	11.88
10.190	2.121	343.85	325.93	325.96	3483.8	19.31	4691	0.665	2437	14.97	1.10	1.81	11.58	12.75	13.25
12.700	2.096	351.70	334.28	334.31	3483.2	19.80	4612	0.665	2413	14.57	1.10	2.21	11.58	14.99	15.42
15.215	2.070	349.90	341.77	341.80	3482.5	20.24	4543	0.665	3943	23.46	1.10	2.58	11.58	35.23	35.42
0.000	-2.070	307.78	292.44	292.47	3486.6	17.34	5046	0.665	2070	13.66	1.10	0.57	11.58	10.46	11.07
7.620	-2.146	336.42	317.19	317.22	3484.5	18.80	4779	0.665	2294	14.35	1.10	1.44	11.58	10.54	11.14
15.240	-2.096	349.37	341.83	341.86	3482.5	20.24	4542	0.665	4223	25.12	1.10	2.58	11.58	37.95	38.12
7.620	3.620	335.85	317.19	317.22	3484.5	18.80	4779	0.665	2365	14.80	1.10	1.44	11.58	10.80	11.39
7.620	-3.620	338.40	317.19	317.22	3484.5	18.80	4779	0.665	2080	13.01	1.10	1.44	11.58	9.76	10.40

Table 3 (continued)

Tube Specimen
Date: 9 March 1990
Time: 10:24:41

TA	TB	M	PA	PA-PB	Vf	Qt	Wqt
K	K	kg/h	kPa	kPa	%	W	%
295.04	551.91	5.25	3546.4	8.8	19.94	1870.0	1.14

Hot-side Temperatures:

X	Y	Tw
cm	cm	K
1.270	-0.762	396.76
2.515	-0.762	429.34
5.080	-0.381	482.83
7.620	-0.381	528.50
10.185	-0.381	570.10
12.700	-0.381	604.56
13.970	-0.381	609.95
7.595	-3.048	527.34

Insulated-Side Temperatures and Calculated Data:

												--------Uncertainties----------				
X	Y	Tw	Tf	Taw	P	V	RE	PR	h	NU	Wtw	Wtf	Wre	Wh	Wnu
cm	cm	K	K	K	kPa	m/s			W/(m²·K)		K	K	%	%	%
-0.020	0.191	349.58	300.72	300.74	3545.4	16.12	4554	0.665	0	0.00	1.10	0.74	11.58	5.35	6.45
1.288	0.191	395.28	318.80	318.82	3544.9	17.08	4378	0.665	2377	14.82	1.10	1.93	11.58	5.70	6.74
2.586	0.140	429.35	339.51	339.54	3544.4	18.17	4195	0.665	2167	12.95	1.10	2.78	11.58	5.66	6.71
3.810	0.165	456.52	359.83	359.86	3544.0	19.24	4032	0.665	2056	11.81	1.10	3.71	11.58	6.03	7.02
5.042	0.191	480.29	380.57	380.60	3543.5	20.34	3881	0.665	2012	11.13	1.10	4.74	11.58	6.62	7.54
6.350	0.203	504.57	402.76	402.80	3543.0	21.51	3733	0.666	1984	10.55	1.10	5.88	11.58	7.37	8.20
7.620	0.191	527.04	424.40	424.45	3542.6	22.65	3601	0.666	1973	10.13	1.10	7.01	11.58	8.22	8.97
8.903	0.152	547.78	446.27	446.32	3542.1	23.81	3479	0.666	1990	9.86	1.10	7.91	11.58	9.04	9.73
10.160	0.216	567.67	467.58	467.64	3541.7	24.93	3368	0.666	2003	9.61	1.18	8.85	11.58	9.98	10.61
11.430	0.191	587.81	488.90	488.96	3541.2	26.06	3266	0.666	2001	9.32	1.26	9.84	11.58	11.00	11.58
12.637	0.140	602.39	508.82	508.88	3540.8	27.11	3177	0.666	2066	9.35	1.32	10.79	11.58	12.50	13.01
13.912	0.165	608.69	529.01	529.07	3540.3	28.18	3093	0.666	2269	10.00	1.34	11.77	11.58	15.67	16.08
15.240	0.165	588.19	547.58	547.65	3539.8	29.16	3019	0.666	3594	15.47	1.26	12.67	11.58	32.06	32.26
-0.036	2.083	353.41	300.72	300.74	3545.4	16.12	4554	0.665	0	0.00	1.10	0.74	11.58	5.26	6.38
2.510	2.108	427.02	338.26	338.29	3544.4	18.10	4205	0.665	2189	13.11	1.10	2.71	11.58	5.65	6.71
5.105	2.070	481.37	381.63	381.67	3543.5	20.39	3873	0.665	2013	11.11	1.10	4.79	11.58	6.66	7.57
7.650	2.096	527.06	424.91	424.96	3542.6	22.68	3598	0.666	1983	10.17	1.10	7.03	11.58	8.26	9.01
10.190	2.121	568.19	468.09	468.14	3541.7	24.96	3366	0.666	2002	9.60	1.18	8.87	11.58	10.00	10.63
12.700	2.096	603.79	509.84	509.90	3540.7	27.17	3173	0.666	2054	9.29	1.32	10.84	11.58	12.51	13.02
15.215	2.070	591.34	547.27	547.34	3539.8	29.15	3021	0.666	3334	14.35	1.27	12.66	11.58	29.60	29.82
0.000	-2.070	360.51	300.72	300.74	3545.3	16.12	4554	0.665	2436	15.80	1.10	1.44	11.58	7.16	8.02
7.620	-2.146	524.62	424.40	424.45	3542.6	22.65	3601	0.666	2021	10.37	1.10	7.01	11.58	8.36	9.10
15.240	-2.096	583.08	547.58	547.65	3539.8	29.16	3019	0.666	4113	17.70	1.24	12.67	11.58	36.50	36.68
7.620	3.620	530.73	424.40	424.45	3542.6	22.65	3601	0.666	1905	9.77	1.10	7.01	11.58	8.02	8.79
7.620	-3.620	529.24	424.40	424.45	3542.6	22.65	3601	0.666	1932	9.91	1.10	7.01	11.58	8.10	8.86

Table 3 (continued)

Tube Specimen
Date: 9 March 1990
Time: 10:33:45

TA	TB	M	PA	PA-PB	Vf	Qt	Wqt
K	K	kg/h	kPa	kPa	%	W	%
290.96	429.78	10.19	3542.6	24.4	19.95	1958.0	1.23

Hot-side Temperatures:

X	Y	Tw
cm	cm	K
1.270	-0.762	347.72
2.515	-0.762	364.34
5.080	-0.381	391.73
7.620	-0.381	415.89
10.185	-0.381	437.44
12.700	-0.381	455.85
13.970	-0.381	459.34
7.595	-3.048	415.08

Insulated-Side Temperatures and Calculated Data:

											---------Uncertainties----------				
X	Y	Tw	Tf	Taw	P	V	RE	PR	h	NU	Wtw	Wtf	Wre	Wh	Wnu
cm	cm	K	K	K	kPa	m/s			W/(m²·K)		K	K	%	%	%
-0.020	0.191	319.84	293.82	293.90	3539.4	30.60	8966	0.665	0	0.00	1.10	0.58	11.58	6.65	7.57
1.288	0.191	346.39	303.58	303.66	3538.1	31.61	8773	0.665	4452	28.68	1.10	1.11	11.58	6.14	7.12
2.586	0.140	363.89	314.75	314.85	3536.8	32.77	8561	0.665	4154	26.12	1.10	1.54	11.58	6.01	7.01
3.810	0.165	377.47	325.72	325.82	3535.6	33.90	8365	0.665	4027	24.75	1.10	2.03	11.58	6.37	7.32
5.042	0.191	389.56	336.91	337.02	3534.4	35.06	8175	0.665	3996	24.00	1.10	2.58	11.58	6.97	7.85
6.350	0.203	402.35	348.89	349.00	3533.1	36.30	7983	0.665	3961	23.24	1.10	3.19	11.58	7.74	8.54
7.620	0.191	414.23	360.57	360.69	3531.9	37.51	7806	0.665	3958	22.70	1.10	3.80	11.58	8.62	9.35
8.903	0.152	425.23	372.37	372.50	3530.6	38.73	7637	0.665	4008	22.49	1.10	4.28	11.58	9.50	10.16
10.160	0.216	435.57	383.87	384.01	3529.4	39.92	7479	0.666	4068	22.36	1.10	4.79	11.58	10.54	11.14
11.430	0.191	446.33	395.38	395.52	3528.2	41.12	7330	0.666	4076	21.96	1.10	5.32	11.58	11.62	12.17
12.637	0.140	454.02	406.12	406.27	3527.0	42.23	7196	0.666	4235	22.40	1.10	5.84	11.58	13.27	13.75
13.912	0.165	457.97	417.02	417.18	3525.8	43.36	7066	0.666	4636	24.08	1.10	6.37	11.58	16.59	16.98
15.240	0.165	446.30	427.04	427.20	3524.5	44.41	6952	0.666	7987	40.81	1.10	6.86	11.58	36.92	37.09
-0.036	2.083	322.99	293.82	293.90	3539.4	30.60	8966	0.665	0	0.00	1.10	0.58	11.58	6.30	7.26
2.510	2.108	362.77	314.08	314.17	3536.9	32.70	8574	0.665	4183	26.34	1.10	1.51	11.58	6.00	7.00
5.105	2.070	390.48	337.49	337.59	3534.4	35.12	8166	0.665	3972	23.83	1.10	2.61	11.58	6.99	7.86
7.650	2.096	414.81	360.85	360.96	3531.9	37.53	7802	0.665	3935	22.56	1.10	3.81	11.58	8.61	9.33
10.190	2.121	436.67	384.14	384.28	3529.4	39.95	7476	0.666	4003	21.99	1.10	4.80	11.58	10.42	11.03
12.700	2.096	455.75	406.68	406.83	3526.9	42.29	7189	0.666	4125	21.80	1.10	5.86	11.58	13.05	13.54
15.215	2.070	449.70	426.87	427.04	3524.5	44.39	6954	0.666	6776	34.63	1.10	6.85	11.58	31.25	31.46
0.000	-2.070	328.52	293.82	293.90	3539.3	30.60	8966	0.665	4402	28.97	1.10	0.88	11.58	7.68	8.48
7.620	-2.146	412.19	360.57	360.69	3531.9	37.51	7806	0.665	4115	23.60	1.10	3.80	11.58	8.88	9.58
15.240	-2.096	442.99	427.04	427.20	3524.5	44.41	6952	0.666	9660	49.36	1.10	6.86	11.58	44.43	44.58
7.620	3.620	418.75	360.57	360.69	3531.9	37.51	7806	0.665	3650	20.94	1.10	3.80	11.58	8.14	8.90
7.620	-3.620	417.47	360.57	360.69	3531.9	37.51	7806	0.665	3732	21.41	1.10	3.80	11.58	8.27	9.02

Table 3 (continued)

Tube Specimen
Date: 9 March 1990
Time: 10:41:50

TA	TB	M	PA	PA-PB	Vf	Qt	Wqt
K	K	kg/h	kPa	kPa	%	W	%
286.47	366.54	17.58	3540.2	59.1	19.96	1945.0	1.44

Hot-side Temperatures:

X	Y	Tw
cm	cm	K
1.270	-0.762	323.22
2.515	-0.762	333.12
5.080	-0.381	349.18
7.620	-0.381	363.39
10.185	-0.381	375.86
12.700	-0.381	386.95
13.970	-0.381	389.22
7.595	-3.048	343.89

Insulated-Side Temperatures and Calculated Data:

											--------Uncertainties---------				
X	Y	Tw	Tf	Taw	P	V	RE	PR	h	NU	Wtw	Wtf	Wre	Wh	Wnu
cm	cm	K	K	K	kPa	m/s			W/(m²·K)		K	K	%	%	%
-0.020	0.191	304.35	287.93	288.15	3531.7	51.88	15681	0.664	0	0.00	1.10	0.53	11.58	8.83	9.54
1.288	0.191	321.99	293.54	293.77	3528.7	52.92	15483	0.665	6698	44.10	1.10	0.75	11.58	6.85	7.74
2.586	0.140	332.58	299.97	300.21	3525.7	54.10	15263	0.665	6254	40.62	1.10	0.96	11.58	6.48	7.42
3.810	0.165	340.59	306.27	306.53	3522.9	55.26	15050	0.665	6067	38.86	1.10	1.22	11.58	6.65	7.56
5.042	0.191	347.55	312.71	312.98	3520.1	56.45	14840	0.665	6036	38.12	1.10	1.51	11.58	7.08	7.94
6.350	0.203	354.86	319.60	319.88	3517.1	57.72	14623	0.665	6003	37.36	1.10	1.86	11.58	7.66	8.47
7.620	0.191	361.47	326.32	326.61	3514.1	58.96	14418	0.665	6040	37.07	1.10	2.20	11.58	8.39	9.13
8.903	0.152	367.68	333.10	333.41	3511.2	60.22	14218	0.665	6126	37.08	1.10	2.48	11.58	9.13	9.81
10.160	0.216	373.55	339.72	340.03	3508.3	61.44	14030	0.665	6219	37.14	1.10	2.77	11.58	10.00	10.63
11.430	0.191	380.31	346.33	346.66	3505.4	62.67	13847	0.665	6116	36.06	1.10	3.08	11.58	10.76	11.35
12.637	0.140	385.20	352.51	352.86	3502.6	63.82	13681	0.665	6211	36.18	1.10	3.38	11.58	11.95	12.48
13.912	0.165	387.65	358.78	359.13	3499.7	64.99	13518	0.665	6588	37.92	1.10	3.68	11.58	14.38	14.83
15.240	0.165	378.77	364.54	364.91	3496.6	66.08	13372	0.665	10930	62.23	1.10	3.97	11.58	30.39	30.60
-0.036	2.083	307.55	287.93	288.15	3531.7	51.88	15681	0.664	0	0.00	1.10	0.53	11.58	7.81	8.60
2.510	2.108	331.88	299.58	299.83	3525.9	54.03	15276	0.665	6301	40.95	1.10	0.94	11.58	6.49	7.43
5.105	2.070	347.64	313.04	313.31	3519.9	56.51	14829	0.665	6079	38.37	1.10	1.53	11.58	7.14	7.99
7.650	2.096	361.26	326.48	326.77	3514.1	58.99	14413	0.665	6104	37.45	1.10	2.21	11.58	8.47	9.20
10.190	2.121	373.91	339.87	340.19	3508.2	61.47	14025	0.665	6179	36.90	1.10	2.78	11.58	9.97	10.61
12.700	2.096	385.71	352.83	353.17	3502.5	63.88	13673	0.665	6163	35.88	1.10	3.39	11.58	11.93	12.46
15.215	2.070	380.85	364.44	364.81	3496.7	66.06	13374	0.665	9514	54.18	1.10	3.96	11.58	26.43	26.67
0.000	-2.070	313.69	287.93	288.15	3531.7	51.88	15681	0.664	5930	39.52	1.10	0.65	11.58	8.24	9.00
7.620	-2.146	360.27	326.32	326.61	3514.1	58.96	14418	0.665	6254	38.38	1.10	2.20	11.58	8.60	9.33
15.240	-2.096	376.68	364.54	364.91	3496.6	66.08	13372	0.665	12867	73.26	1.10	3.97	11.58	35.55	35.73
7.620	3.620	364.87	326.32	326.61	3514.1	58.96	14418	0.665	5503	33.77	1.10	2.20	11.58	7.87	8.66
7.620	-3.620	366.24	326.32	326.61	3514.1	58.96	14418	0.665	5312	32.60	1.10	2.20	11.58	7.69	8.49

Table 3 (continued)

Tube Specimen
Date: 9 March 1990
Time: 10:48:18

TA	TB	M	PA	PA-PB	Vf	Qt	Wqt
K	K	kg/h	kPa	kPa	%	W	%
283.68	335.13	27.14	3538.6	124.8	19.95	1925.0	1.81

Hot-side Temperatures:

X	Y	Tw
cm	cm	K
1.270	-0.762	310.09
2.515	-0.762	316.64
5.080	-0.381	327.26
7.620	-0.381	336.57
10.185	-0.381	344.43
12.700	-0.381	351.51
13.970	-0.381	352.94
7.595	-3.048	323.81

Insulated-Side Temperatures and Calculated Data:

											---------Uncertainties----------				
X	Y	Tw	Tf	Taw	P	V	RE	PR	h	NU	Wtw	Wtf	Wre	Wh	Wnu
cm	cm	K	K	K	kPa	m/s			W/(m²·K)		K	K	%	%	%
-0.020	0.191	296.03	284.20	284.72	3519.9	79.34	24418	0.664	0	0.00	1.10	0.51	11.58	11.68	12.22
1.288	0.191	308.80	287.79	288.33	3513.7	80.46	24217	0.664	9137	60.92	1.10	0.60	11.58	7.96	8.74
2.586	0.140	315.79	291.90	292.46	3507.6	81.73	23992	0.665	8587	56.75	1.10	0.70	11.58	7.35	8.19
3.810	0.165	321.05	295.93	296.51	3501.8	82.97	23776	0.665	8338	54.62	1.10	0.84	11.58	7.35	8.19
5.042	0.191	325.61	300.05	300.65	3495.9	84.25	23559	0.665	8274	53.73	1.10	1.01	11.58	7.61	8.42
6.350	0.203	330.48	304.45	305.07	3489.7	85.61	23329	0.665	8183	52.62	1.10	1.22	11.58	7.98	8.76
7.620	0.191	334.82	308.75	309.39	3483.7	86.94	23109	0.665	8195	52.21	1.10	1.44	11.58	8.51	9.24
8.903	0.152	338.76	313.09	313.75	3477.6	88.30	22893	0.665	8311	52.46	1.10	1.62	11.58	9.10	9.79
10.160	0.216	342.34	317.32	318.00	3471.7	89.62	22686	0.665	8476	53.01	1.10	1.80	11.58	9.86	10.50
11.430	0.191	346.78	321.55	322.25	3465.7	90.95	22483	0.665	8302	51.47	1.10	2.00	11.58	10.44	11.04
12.637	0.140	349.90	325.51	326.22	3459.9	92.20	22298	0.665	8399	51.64	1.10	2.19	11.58	11.42	11.98
13.912	0.165	351.34	329.51	330.25	3453.9	93.48	22114	0.665	8816	53.76	1.10	2.39	11.58	13.48	13.95
15.240	0.165	344.65	333.20	333.95	3447.6	94.68	21948	0.665	14017	84.84	1.10	2.57	11.58	26.95	27.19
-0.036	2.083	299.04	284.20	284.72	3520.0	79.33	24418	0.664	0	0.00	1.10	0.51	11.58	9.66	10.31
2.510	2.108	315.29	291.65	292.21	3507.9	81.65	24005	0.665	8661	57.27	1.10	0.69	11.58	7.39	8.22
5.105	2.070	325.52	300.26	300.86	3495.6	84.31	23548	0.665	8377	54.38	1.10	1.02	11.58	7.69	8.49
7.650	2.096	334.45	308.85	309.49	3483.6	86.98	23104	0.665	8350	53.18	1.10	1.44	11.58	8.63	9.36
10.190	2.121	342.43	317.42	318.10	3471.5	89.65	22681	0.665	8477	53.01	1.10	1.81	11.58	9.88	10.52
12.700	2.096	350.14	325.71	326.42	3459.6	92.26	22289	0.665	8370	51.44	1.10	2.20	11.58	11.44	12.00
15.215	2.070	346.27	333.13	333.89	3447.7	94.66	21951	0.665	12200	73.85	1.10	2.57	11.58	23.49	23.77
0.000	-2.070	304.64	284.20	284.72	3519.8	79.34	24418	0.664	7528	50.60	1.10	0.57	11.58	9.10	9.78
7.620	-2.146	333.80	308.75	309.39	3483.7	86.94	23109	0.665	8538	54.39	1.10	1.44	11.58	8.76	9.47
15.240	-2.096	343.12	333.20	333.95	3447.6	94.68	21948	0.665	16361	99.02	1.10	2.57	11.58	31.21	31.42
7.620	3.620	337.88	308.75	309.39	3483.7	86.94	23109	0.665	7316	46.61	1.10	1.44	11.58	7.88	8.67
7.620	-3.620	339.26	308.75	309.39	3483.7	86.94	23109	0.665	6977	44.45	1.10	1.44	11.58	7.65	8.45

Table 3 (continued)

Tube Specimen
Date: 9 March 1990
Time: 10:54:34

TA	TB	M	PA	PA-PB	Vf	Qt	Wqt
K	K	kg/h	kPa	kPa	%	W	%
281.76	317.18	39.04	3535.8	242.8	19.97	1901.0	2.37

Hot-side Temperatures:

X	Y	Tw
cm	cm	K
1.270	-0.762	301.79
2.515	-0.762	306.40
5.080	-0.381	313.99
7.620	-0.381	320.79
10.185	-0.381	325.97
12.700	-0.381	330.61
13.970	-0.381	331.76
7.595	-3.048	312.24

Insulated-Side Temperatures and Calculated Data:

											--------Uncertainties---------				
X	Y	Tw	Tf	Taw	P	V	RE	PR	h	NU	Wtw	Wtf	Wre	Wh	Wnu
cm	cm	K	K	K	kPa	m/s			W/(m²·K)		K	K	%	%	%
-0.020	0.191	290.77	281.30	282.39	3498.8	113.69	35373	0.664	0	0.00	1.10	0.50	11.58	15.16	15.58
1.288	0.191	300.58	283.75	284.87	3486.9	115.04	35172	0.664	11749	79.06	1.10	0.53	11.58	9.43	10.09
2.586	0.140	305.62	286.56	287.70	3475.1	116.54	34946	0.664	11039	73.82	1.10	0.57	11.58	8.55	9.28
3.810	0.165	309.31	289.31	290.48	3464.0	118.01	34727	0.664	10726	71.29	1.10	0.64	11.58	8.39	9.13
5.042	0.191	312.42	292.12	293.32	3452.9	119.52	34506	0.665	10676	70.53	1.10	0.75	11.58	8.53	9.26
6.350	0.203	315.84	295.13	296.36	3441.0	121.14	34275	0.665	10534	69.14	1.10	0.88	11.58	8.74	9.45
7.620	0.191	318.91	298.06	299.32	3429.5	122.72	34052	0.665	10506	68.53	1.10	1.02	11.58	9.10	9.78
8.903	0.152	321.64	301.02	302.32	3417.9	124.33	33829	0.665	10618	68.82	1.10	1.14	11.58	9.55	10.21
10.160	0.216	324.05	303.90	305.23	3406.5	125.92	33613	0.665	10823	69.71	1.10	1.27	11.58	10.19	10.81
11.430	0.191	327.15	306.79	308.15	3394.9	127.52	33399	0.665	10583	67.73	1.10	1.40	11.58	10.62	11.21
12.637	0.140	329.26	309.48	310.88	3384.0	129.03	33203	0.665	10680	67.95	1.10	1.53	11.58	11.45	12.01
13.912	0.165	330.20	312.21	313.64	3372.4	130.59	33007	0.665	11091	70.15	1.10	1.67	11.58	13.22	13.71
15.240	0.165	324.98	314.72	316.18	3360.4	132.08	32829	0.665	16844	105.98	1.10	1.80	11.58	24.94	25.20
-0.036	2.083	293.62	281.30	282.39	3498.9	113.68	35373	0.664	0	0.00	1.10	0.50	11.58	11.73	12.27
2.510	2.108	305.27	286.39	287.53	3475.8	116.46	34959	0.664	11127	74.43	1.10	0.56	11.58	8.60	9.33
5.105	2.070	312.52	292.27	293.47	3452.3	119.60	34495	0.665	10705	70.70	1.10	0.75	11.58	8.56	9.29
7.650	2.096	318.95	298.13	299.39	3429.2	122.76	34047	0.665	10523	68.63	1.10	1.02	11.58	9.11	9.80
10.190	2.121	324.39	303.97	305.30	3406.2	125.96	33607	0.665	10668	68.70	1.10	1.27	11.58	10.09	10.71
12.700	2.096	329.77	309.62	311.02	3383.4	129.10	33193	0.665	10447	66.45	1.10	1.54	11.58	11.30	11.86
15.215	2.070	326.50	314.68	316.14	3360.6	132.06	32832	0.665	14396	90.58	1.10	1.80	11.58	21.43	21.73
0.000	-2.070	298.83	281.30	282.39	3498.6	113.69	35373	0.664	9002	60.91	1.10	0.53	11.58	10.09	10.71
7.620	-2.146	318.10	298.06	299.32	3429.5	122.72	34052	0.665	10959	71.48	1.10	1.02	11.58	9.38	10.04
15.240	-2.096	323.67	314.72	316.18	3360.4	132.08	32829	0.665	19772	124.40	1.10	1.80	11.58	28.98	29.21
7.620	3.620	322.19	298.06	299.32	3429.5	122.72	34052	0.665	8998	58.70	1.10	1.02	11.58	8.19	8.95
7.620	-3.620	322.96	298.06	299.32	3429.5	122.72	34052	0.665	8706	56.79	1.10	1.02	11.58	8.02	8.79

Table 3 (continued)

Tube Specimen
Date: 9 March 1990
Time: 11:07:53

TA	TB	M	PA	PA-PB	Vf	Qt	Wqt
K	K	kg/h	kPa	kPa	%	W	%
290.15	471.21	7.57	3578.0	15.5	19.97	1896.0	1.18

Hot-side Temperatures:

X	Y	Tw
cm	cm	K
1.270	-0.762	363.59
2.515	-0.762	386.33
5.080	-0.381	423.55
7.620	-0.381	455.69
10.185	-0.381	485.05
12.700	-0.381	509.76
13.970	-0.381	514.31
7.595	-3.048	412.97

Insulated-Side Temperatures and Calculated Data:

											---------Uncertainties----------				
X	Y	Tw	Tf	Taw	P	V	RE	PR	h	NU	Wtw	Wtf	Wre	Wh	Wnu
cm	cm	K	K	K	kPa	m/s			W/(m²·K)		K	K	%	%	%
-0.020	0.191	328.26	294.07	294.11	3576.0	22.53	6657	0.665	0	0.00	1.10	0.63	11.58	5.92	6.93
1.288	0.191	362.40	306.79	306.84	3575.2	23.49	6471	0.665	3317	21.21	1.10	1.40	11.58	5.86	6.88
2.586	0.140	386.32	321.37	321.42	3574.4	24.59	6271	0.665	3041	18.85	1.10	1.98	11.58	5.77	6.80
3.810	0.165	405.11	335.67	335.73	3573.6	25.67	6089	0.665	2904	17.48	1.10	2.63	11.58	6.10	7.09
5.042	0.191	421.50	350.27	350.33	3572.8	26.78	5915	0.665	2858	16.72	1.10	3.35	11.58	6.68	7.59
6.350	0.203	438.40	365.89	365.95	3572.0	27.96	5742	0.665	2826	16.05	1.10	4.14	11.58	7.41	8.24
7.620	0.191	454.09	381.12	381.20	3571.2	29.11	5584	0.665	2816	15.55	1.10	4.94	11.58	8.25	9.00
8.903	0.152	468.60	396.52	396.59	3570.4	30.28	5435	0.666	2843	15.28	1.10	5.57	11.58	9.06	9.75
10.160	0.216	482.58	411.52	411.60	3569.6	31.41	5298	0.666	2863	15.00	1.10	6.24	11.58	9.99	10.62
11.430	0.191	497.14	426.52	426.61	3568.8	32.55	5169	0.666	2844	14.55	1.10	6.93	11.58	10.93	11.51
12.637	0.140	507.97	440.54	440.63	3568.0	33.61	5056	0.666	2909	14.55	1.10	7.60	11.58	12.31	12.82
13.912	0.165	512.97	454.75	454.85	3567.2	34.69	4946	0.666	3152	15.42	1.10	8.29	11.58	15.21	15.64
15.240	0.165	498.20	467.82	467.93	3566.4	35.69	4850	0.666	4880	23.42	1.10	8.93	11.58	30.39	30.61
-0.036	2.083	331.47	294.07	294.11	3576.0	22.53	6657	0.665	0	0.00	1.10	0.63	11.58	5.74	6.77
2.510	2.108	384.50	320.49	320.55	3574.4	24.52	6283	0.665	3079	19.13	1.10	1.94	11.58	5.77	6.80
5.105	2.070	422.18	351.02	351.08	3572.8	26.83	5907	0.665	2862	16.72	1.10	3.38	11.58	6.72	7.62
7.650	2.096	453.93	381.48	381.56	3571.2	29.14	5580	0.665	2836	15.65	1.10	4.95	11.58	8.30	9.05
10.190	2.121	483.08	411.87	411.96	3569.6	31.44	5295	0.666	2856	14.96	1.10	6.25	11.58	9.99	10.62
12.700	2.096	508.86	441.26	441.36	3568.0	33.67	5050	0.666	2896	14.47	1.10	7.64	11.58	12.33	12.85
15.215	2.070	500.70	467.60	467.71	3566.4	35.67	4852	0.666	4510	21.65	1.10	8.92	11.58	27.97	28.20
0.000	-2.070	338.35	294.07	294.11	3576.0	22.53	6657	0.665	3338	21.95	1.10	1.07	11.58	7.37	8.20
7.620	-2.146	452.19	381.12	381.20	3571.2	29.11	5584	0.665	2891	15.97	1.10	4.94	11.58	8.40	9.14
15.240	-2.096	494.64	467.82	467.93	3566.4	35.69	4850	0.666	5531	26.54	1.10	8.93	11.58	34.28	34.47
7.620	3.620	457.76	381.12	381.20	3571.2	29.11	5584	0.665	2681	14.81	1.10	4.94	11.58	7.97	8.75
7.620	-3.620	457.65	381.12	381.20	3571.2	29.11	5584	0.665	2685	14.83	1.10	4.94	11.58	7.98	8.75

Table 3 (continued)

Tube Specimen
Date: 16 February 1990
Time: 14:45:04

TA	TB	M	PA	PA-PB	Vf	Qt	Wqt
K	K	kg/h	kPa	kPa	%	W	%
287.91	594.95	8.57	3494.1	22.2	34.97	3629.0	1.14

Hot-side Temperatures:

X	Y	Tw
cm	cm	K
1.270	-0.762	418.81
2.515	-0.762	457.21
5.080	-0.381	517.14
7.620	-0.381	569.60
10.185	-0.381	618.08
12.700	-0.381	658.80
13.970	-0.381	667.85
7.595	-3.048	515.39

Insulated-Side Temperatures and Calculated Data:

											--------Uncertainties----------				
X	Y	Tw	Tf	Taw	P	V	RE	PR	h	NU	Wtw	Wtf	Wre	Wh	Wnu
cm	cm	K	K	K	kPa	m/s			W/(m²·K)		K	K	%	%	%
-0.020	0.191	355.33	295.40	295.45	3491.4	26.23	7516	0.665	0	0.00	1.10	0.82	11.58	4.81	6.01
1.288	0.191	415.32	317.32	317.39	3490.2	28.15	7163	0.665	3542	22.15	1.10	2.27	11.58	5.54	6.61
2.586	0.140	455.98	341.20	341.28	3489.1	30.24	6819	0.665	3167	18.86	1.10	3.24	11.58	5.58	6.64
3.810	0.165	486.09	364.46	364.54	3488.0	32.28	6519	0.665	3059	17.42	1.10	4.33	11.58	5.91	6.92
5.042	0.191	512.08	388.34	388.44	3486.9	34.38	6242	0.666	3062	16.70	1.10	5.52	11.58	6.45	7.39
6.350	0.203	539.50	414.10	414.21	3485.8	36.64	5973	0.666	3062	15.98	1.10	6.86	11.58	7.15	8.01
7.620	0.191	564.91	439.36	439.49	3484.7	38.85	5735	0.666	3078	15.43	1.17	8.18	11.58	7.98	8.75
8.903	0.152	589.28	464.97	465.12	3483.5	41.10	5515	0.666	3116	15.02	1.26	9.23	11.58	8.74	9.46
10.160	0.216	612.49	490.13	490.29	3482.4	43.32	5318	0.666	3177	14.77	1.36	10.34	11.58	9.64	10.29
11.430	0.191	635.90	515.69	515.87	3481.3	45.57	5134	0.666	3262	14.63	1.45	11.53	11.58	10.66	11.25
12.637	0.140	653.51	540.16	540.35	3480.2	47.72	4971	0.666	3466	15.06	1.52	12.71	11.58	12.16	12.68
13.912	0.165	663.19	565.57	565.78	3479.1	49.96	4815	0.666	3840	16.16	1.56	13.95	11.58	15.15	15.57
15.240	0.165	637.99	588.98	589.21	3477.9	52.02	4681	0.666	6002	24.55	1.46	15.08	11.58	31.75	31.95
-0.036	2.083	371.07	295.40	295.45	3491.4	26.23	7516	0.665	0	0.00	1.10	0.82	11.58	4.61	5.85
2.510	2.108	451.27	339.78	339.86	3489.2	30.12	6838	0.665	3255	19.44	1.10	3.19	11.58	5.61	6.67
5.105	2.070	511.52	389.57	389.67	3486.9	34.48	6229	0.666	3109	16.92	1.10	5.59	11.58	6.53	7.46
7.650	2.096	562.91	439.96	440.08	3484.6	38.91	5729	0.666	3144	15.74	1.16	8.20	11.58	8.11	8.87
10.190	2.121	610.35	490.73	490.89	3482.4	43.37	5313	0.666	3251	15.09	1.35	10.37	11.58	9.83	10.47
12.700	2.096	652.23	541.43	541.63	3480.2	47.83	4963	0.666	3544	15.37	1.52	12.77	11.58	12.45	12.96
15.215	2.070	640.69	588.60	588.83	3478.0	51.99	4683	0.666	5695	23.30	1.47	15.06	11.58	29.90	30.11
0.000	-2.070	393.98	295.40	295.45	3491.4	26.23	7516	0.665	3101	20.34	1.10	1.79	11.58	6.03	7.03
7.620	-2.146	570.27	439.36	439.49	3484.7	38.85	5735	0.666	2952	14.79	1.19	8.18	11.58	7.76	8.55
15.240	-2.096	639.24	588.98	589.21	3477.9	52.02	4681	0.666	5853	23.94	1.46	15.08	11.58	30.99	31.20
7.620	3.620	571.62	439.36	439.49	3484.7	38.85	5735	0.666	2922	14.64	1.19	8.18	11.58	7.71	8.51
7.620	-3.620	589.02	439.36	439.49	3484.7	38.85	5735	0.666	2582	12.94	1.26	8.18	11.58	7.13	7.99

Table 3 (continued)

Tube Specimen
Date: 16 February 1990
Time: 14:53:29

TA	TB	M	PA	PA-PB	Vf	Qt	Wqt
K	K	kg/h	kPa	kPa	%	W	%
285.37	502.70	12.50	3494.5	38.4	34.97	3745.0	1.16

Hot-side Temperatures:

X	Y	Tw
cm	cm	K
1.270	-0.762	381.48
2.515	-0.762	408.07
5.080	-0.381	450.29
7.620	-0.381	487.81
10.185	-0.381	521.44
12.700	-0.381	549.29
13.970	-0.381	556.09
7.595	-3.048	424.13

Insulated-Side Temperatures and Calculated Data:

											--------Uncertainties---------				
X	Y	Tw	Tf	Taw	P	V	RE	PR	h	NU	Wtw	Wtf	Wre	Wh	Wnu
cm	cm	K	K	K	kPa	m/s			W/(m²·K)		K	K	%	%	%
-0.020	0.191	333.66	290.41	290.53	3489.6	37.64	11088	0.664	0	0.00	1.10	0.68	11.58	5.18	6.31
1.288	0.191	378.39	305.92	306.05	3487.6	39.64	10710	0.665	4949	31.72	1.10	1.64	11.58	5.62	6.68
2.586	0.140	407.04	322.81	322.95	3485.7	41.81	10328	0.665	4459	27.57	1.10	2.31	11.58	5.62	6.68
3.810	0.165	427.79	339.25	339.41	3483.9	43.93	9985	0.665	4342	25.96	1.10	3.08	11.58	5.93	6.94
5.042	0.191	445.84	356.14	356.32	3482.0	46.11	9660	0.665	4364	25.24	1.10	3.92	11.58	6.45	7.39
6.350	0.203	465.28	374.35	374.55	3480.1	48.46	9337	0.666	4364	24.40	1.10	4.86	11.58	7.11	7.97
7.620	0.191	483.12	392.22	392.43	3478.2	50.76	9044	0.666	4394	23.80	1.10	5.79	11.58	7.91	8.69
8.903	0.152	500.16	410.33	410.57	3476.2	53.10	8768	0.666	4457	23.41	1.10	6.54	11.58	8.66	9.38
10.160	0.216	516.36	428.11	428.37	3474.4	55.40	8516	0.666	4554	23.23	1.10	7.32	11.58	9.54	10.19
11.430	0.191	532.52	446.19	446.47	3472.5	57.75	8277	0.666	4696	23.28	1.10	8.17	11.58	10.56	11.16
12.637	0.140	544.68	463.49	463.79	3470.7	59.99	8063	0.666	5004	24.17	1.10	9.00	11.58	12.06	12.59
13.912	0.165	551.76	481.45	481.78	3468.8	62.32	7854	0.666	5517	25.96	1.11	9.88	11.58	14.95	15.38
15.240	0.165	532.06	498.01	498.36	3466.8	64.48	7672	0.666	8967	41.22	1.10	10.67	11.58	32.52	32.72
-0.036	2.083	348.71	290.41	290.53	3489.6	37.64	11088	0.664	0	0.00	1.10	0.68	11.58	4.78	5.99
2.510	2.108	403.60	321.80	321.95	3485.8	41.68	10350	0.665	4583	28.40	1.10	2.28	11.58	5.65	6.70
5.105	2.070	445.48	357.01	357.19	3481.9	46.22	9644	0.665	4428	25.57	1.10	3.96	11.58	6.52	7.45
7.650	2.096	481.87	392.64	392.86	3478.1	50.82	9037	0.666	4477	24.23	1.10	5.81	11.58	8.03	8.80
10.190	2.121	515.41	428.54	428.80	3474.3	55.46	8510	0.666	4628	23.59	1.10	7.34	11.58	9.67	10.32
12.700	2.096	544.37	464.39	464.69	3470.6	60.11	8052	0.666	5077	24.49	1.10	9.04	11.58	12.27	12.79
15.215	2.070	535.13	497.74	498.09	3466.8	64.44	7675	0.666	8228	37.83	1.10	10.66	11.58	29.66	29.88
0.000	-2.070	369.57	290.41	290.53	3489.5	37.64	11088	0.664	3990	26.45	1.10	1.31	11.58	6.05	7.04
7.620	-2.146	487.27	392.22	392.43	3478.2	50.76	9044	0.666	4202	22.76	1.10	5.79	11.58	7.68	8.48
15.240	-2.096	533.47	498.01	498.36	3466.8	64.48	7672	0.666	8607	39.56	1.10	10.67	11.58	31.27	31.48
7.620	3.620	490.52	392.22	392.43	3478.2	50.76	9044	0.666	4063	22.01	1.10	5.79	11.58	7.51	8.33
7.620	-3.620	506.00	392.22	392.43	3478.2	50.76	9044	0.666	3509	19.01	1.10	5.79	11.58	6.87	7.76

Table 3 (continued)

Tube Specimen
Date: 16 February 1990
Time: 15:01:07

TA	TB	M	PA	PA-PB	Vf	Qt	Wqt
K	K	kg/h	kPa	kPa	%	W	%
281.89	421.92	19.63	3496.0	76.0	34.96	3786.0	1.23

Hot-side Temperatures:

X	Y	Tw
cm	cm	K
1.270	-0.762	349.23
2.515	-0.762	366.57
5.080	-0.381	394.40
7.620	-0.381	419.62
10.185	-0.381	441.29
12.700	-0.381	458.82
13.970	-0.381	463.15
7.595	-3.048	379.51

Insulated-Side Temperatures and Calculated Data:

											---------Uncertainties----------				
X	Y	Tw	Tf	Taw	P	V	RE	PR	h	NU	Wtw	Wtf	Wre	Wh	Wnu
cm	cm	K	K	K	kPa	m/s			W/(m²·K)		K	K	%	%	%
-0.020	0.191	314.69	284.86	285.15	3485.4	58.09	17640	0.664	0	0.00	1.10	0.58	11.58	5.97	6.97
1.288	0.191	346.48	294.83	295.13	3481.7	60.15	17244	0.665	7049	46.29	1.10	1.11	11.58	5.80	6.83
2.586	0.140	365.55	305.68	306.01	3477.9	62.39	16832	0.665	6365	40.83	1.10	1.52	11.58	5.69	6.74
3.810	0.165	378.92	316.25	316.60	3474.4	64.57	16450	0.665	6225	39.02	1.10	2.00	11.58	5.92	6.93
5.042	0.191	390.78	327.10	327.48	3470.9	66.82	16078	0.665	6239	38.23	1.10	2.54	11.58	6.34	7.29
6.350	0.203	403.70	338.81	339.21	3467.2	69.24	15699	0.665	6208	37.15	1.10	3.14	11.58	6.87	7.76
7.620	0.191	415.19	350.29	350.72	3463.5	71.63	15347	0.665	6248	36.56	1.10	3.74	11.58	7.55	8.37
8.903	0.152	426.44	361.93	362.39	3459.8	74.05	15009	0.665	6302	36.06	1.10	4.22	11.58	8.16	8.92
10.160	0.216	436.96	373.36	373.85	3456.2	76.43	14694	0.666	6419	35.96	1.10	4.72	11.58	8.90	9.61
11.430	0.191	447.35	384.97	385.49	3452.6	78.86	14389	0.666	6603	36.23	1.10	5.26	11.58	9.78	10.42
12.637	0.140	455.16	396.08	396.64	3449.1	81.18	14111	0.666	6992	37.63	1.10	5.80	11.58	11.03	11.61
13.912	0.165	459.47	407.63	408.22	3445.5	83.60	13836	0.666	7613	40.17	1.10	6.36	11.58	13.45	13.92
15.240	0.165	444.23	418.26	418.88	3441.7	85.85	13593	0.666	12050	62.46	1.10	6.88	11.58	28.27	28.50
-0.036	2.083	328.51	284.86	285.15	3485.5	58.09	17640	0.664	0	0.00	1.10	0.58	11.58	5.12	6.26
2.510	2.108	363.06	305.04	305.36	3478.2	62.25	16856	0.665	6556	42.11	1.10	1.50	11.58	5.74	6.78
5.105	2.070	390.21	327.66	328.04	3470.7	66.93	16059	0.665	6357	38.91	1.10	2.57	11.58	6.42	7.36
7.650	2.096	414.08	350.56	350.99	3463.4	71.68	15339	0.665	6386	37.34	1.10	3.75	11.58	7.67	8.47
10.190	2.121	436.03	373.63	374.12	3456.2	76.49	14686	0.666	6545	36.65	1.10	4.73	11.58	9.05	9.74
12.700	2.096	454.95	396.67	397.22	3449.0	81.30	14097	0.666	7084	38.08	1.10	5.83	11.58	11.21	11.77
15.215	2.070	446.90	418.09	418.71	3441.7	85.81	13597	0.666	10929	56.67	1.10	6.87	11.58	25.54	25.79
0.000	-2.070	347.53	284.86	285.15	3485.4	58.09	17640	0.664	5109	34.29	1.10	0.93	11.58	6.12	7.10
7.620	-2.146	417.68	350.29	350.72	3463.5	71.63	15347	0.665	6016	35.19	1.10	3.74	11.58	7.37	8.20
15.240	-2.096	444.64	418.26	418.88	3441.7	85.85	13593	0.666	11859	61.47	1.10	6.88	11.58	27.85	28.08
7.620	3.620	422.07	350.29	350.72	3463.5	71.63	15347	0.665	5646	33.03	1.10	3.74	11.58	7.09	7.95
7.620	-3.620	434.92	350.29	350.72	3463.5	71.63	15347	0.665	4784	27.99	1.10	3.74	11.58	6.47	7.41

Table 3 (continued)

Tube Specimen
Date: 16 February 1990
Time: 15:07:14

TA	TB	M	PA	PA-PB	Vf	Qt	Wqt
K	K	kg/h	kPa	kPa	%	W	%
279.20	374.67	28.66	3499.3	139.9	34.98	3761.0	1.36

Hot-side Temperatures:

X	Y	TW
cm	cm	K
1.270	-0.762	329.38
2.515	-0.762	341.39
5.080	-0.381	360.41
7.620	-0.381	377.98
10.185	-0.381	392.60
12.700	-0.381	404.48
13.970	-0.381	407.93
7.595	-3.048	342.42

Insulated-Side Temperatures and Calculated Data:

X	Y	TW	Tf	Taw	P	V	RE	PR	h	NU	Wtw	Wtf	Wre	Wh	Wnu
cm	cm	K	K	K	kPa	m/s			W/(m²·K)		K	K	%	%	%
-0.020	0.191	302.98	280.80	281.39	3478.8	83.76	25996	0.664	0	0.00	1.10	0.54	11.58	7.08	7.94
1.288	0.191	326.83	287.56	288.18	3472.1	85.91	25591	0.664	9304	62.08	1.10	0.83	11.58	6.11	7.10
2.586	0.140	340.61	294.93	295.59	3465.4	88.24	25167	0.665	8362	54.90	1.10	1.08	11.58	5.88	6.89
3.810	0.165	349.19	302.11	302.79	3459.2	90.51	24768	0.665	8305	53.69	1.10	1.39	11.58	6.05	7.04
5.042	0.191	357.09	309.47	310.20	3452.8	92.84	24369	0.665	8367	53.22	1.10	1.75	11.58	6.39	7.33
6.350	0.203	366.00	317.42	318.18	3446.1	95.37	23954	0.665	8316	52.01	1.10	2.15	11.58	6.82	7.71
7.620	0.191	373.80	325.21	326.01	3439.6	97.85	23564	0.665	8374	51.52	1.10	2.56	11.58	7.40	8.23
8.903	0.152	381.56	333.11	333.95	3433.0	100.38	23184	0.665	8424	51.00	1.10	2.88	11.58	7.92	8.70
10.160	0.216	388.62	340.86	341.75	3426.5	102.87	22824	0.665	8587	51.18	1.10	3.22	11.58	8.57	9.30
11.430	0.191	395.90	348.74	349.68	3420.0	105.41	22472	0.665	8778	51.52	1.10	3.59	11.58	9.30	9.97
12.637	0.140	401.08	356.28	357.26	3413.8	107.85	22147	0.665	9277	53.66	1.10	3.96	11.58	10.41	11.01
13.912	0.165	404.16	364.11	365.14	3407.3	110.39	21821	0.666	9935	56.63	1.10	4.34	11.58	12.42	12.94
15.240	0.165	392.33	371.33	372.40	3400.5	112.77	21531	0.666	15228	85.64	1.10	4.70	11.58	25.10	25.36
-0.036	2.083	317.88	280.80	281.39	3478.9	83.76	25996	0.664	0	0.00	1.10	0.54	11.58	5.40	6.50
2.510	2.108	338.24	294.49	295.14	3465.8	88.10	25192	0.665	8719	57.30	1.10	1.07	11.58	5.96	6.97
5.105	2.070	356.73	309.85	310.58	3452.5	92.96	24348	0.665	8507	54.07	1.10	1.77	11.58	6.46	7.40
7.650	2.096	373.15	325.39	326.20	3439.4	97.91	23555	0.665	8524	52.42	1.10	2.57	11.58	7.49	8.31
10.190	2.121	388.21	341.05	341.94	3426.4	102.93	22816	0.665	8698	51.82	1.10	3.23	11.58	8.66	9.38
12.700	2.096	400.98	356.67	357.65	3413.5	107.97	22131	0.665	9378	54.20	1.10	3.98	11.58	10.54	11.14
15.215	2.070	394.47	371.21	372.28	3400.6	112.73	21536	0.666	13793	77.59	1.10	4.69	11.58	22.68	22.97
0.000	-2.070	335.46	280.80	281.39	3478.7	83.77	25996	0.664	5856	39.67	1.10	0.73	11.58	6.20	7.17
7.620	-2.146	376.59	325.21	326.01	3439.6	97.85	23564	0.665	7912	48.68	1.10	2.56	11.58	7.15	8.00
15.240	-2.096	393.15	371.33	372.40	3400.5	112.77	21531	0.666	14621	82.23	1.10	4.70	11.58	24.17	24.44
7.620	3.620	380.52	325.21	326.01	3439.6	97.85	23564	0.665	7342	45.17	1.10	2.56	11.58	6.85	7.74
7.620	-3.620	392.42	325.21	326.01	3439.6	97.85	23564	0.665	6026	37.08	1.10	2.56	11.58	6.19	7.17

Table 3 (continued)

Tube Specimen
Date: 16 February 1990
Time: 15:13:12

TA	TB	M	PA	PA-PB	Vf	Qt	Wqt
K	K	kg/h	kPa	kPa	%	W	%
277.18	347.55	38.84	3502.2	237.0	34.98	3750.0	1.53

Hot-side Temperatures:

X	Y	Tw
cm	cm	K
1.270	-0.762	317.09
2.515	-0.762	326.09
5.080	-0.381	340.43
7.620	-0.381	353.91
10.185	-0.381	364.68
12.700	-0.381	373.01
13.970	-0.381	375.53
7.595	-3.048	328.57

Insulated-Side Temperatures and Calculated Data:

											--------Uncertainties----------				
X	Y	Tw	Tf	Taw	P	V	RE	PR	h	NU	Wtw	Wtf	Wre	Wh	Wnu
cm	cm	K	K	K	kPa	m/s			W/(m²·K)		K	K	%	%	%
-0.020	0.191	295.65	277.65	278.71	3466.5	112.66	35492	0.664	0	0.00	1.10	0.52	11.58	8.34	9.09
1.288	0.191	314.60	282.60	283.71	3455.3	115.00	35082	0.664	11606	78.30	1.10	0.69	11.58	6.54	7.47
2.586	0.140	325.25	288.00	289.16	3444.2	117.53	34647	0.664	10402	69.34	1.10	0.85	11.58	6.17	7.15
3.810	0.165	331.53	293.26	294.47	3433.8	119.99	34237	0.665	10369	68.33	1.10	1.06	11.58	6.28	7.24
5.042	0.191	337.39	298.65	299.91	3423.2	122.53	33827	0.665	10439	68.01	1.10	1.31	11.58	6.54	7.47
6.350	0.203	344.13	304.47	305.79	3412.1	125.28	33392	0.665	10342	66.52	1.10	1.60	11.58	6.87	7.76
7.620	0.191	349.77	310.17	311.55	3401.2	127.98	32976	0.665	10440	66.33	1.10	1.90	11.58	7.36	8.20
8.903	0.152	355.38	315.95	317.39	3390.2	130.74	32567	0.665	10526	66.05	1.10	2.13	11.58	7.82	8.61
10.160	0.216	360.58	321.63	323.13	3379.5	133.47	32177	0.665	10717	66.44	1.10	2.39	11.58	8.39	9.13
11.430	0.191	366.03	327.40	328.96	3368.6	136.26	31792	0.665	10916	66.87	1.10	2.66	11.58	9.01	9.70
12.637	0.140	369.69	332.92	334.54	3358.3	138.94	31434	0.665	11533	69.86	1.10	2.93	11.58	10.00	10.63
13.912	0.165	372.14	338.64	340.33	3347.4	141.75	31072	0.665	12156	72.79	1.10	3.21	11.58	11.70	12.24
15.240	0.165	362.49	343.92	345.67	3336.1	144.40	30747	0.665	17999	106.66	1.10	3.47	11.58	22.67	22.96
-0.036	2.083	309.99	277.65	278.71	3466.6	112.66	35492	0.664	0	0.00	1.10	0.52	11.58	5.75	6.79
2.510	2.108	323.11	287.68	288.84	3444.9	117.38	34673	0.664	10934	72.94	1.10	0.84	11.58	6.30	7.26
5.105	2.070	336.85	298.93	300.19	3422.7	122.66	33806	0.665	10682	69.55	1.10	1.33	11.58	6.63	7.55
7.650	2.096	349.09	310.31	311.69	3401.0	128.05	32966	0.665	10670	67.76	1.10	1.90	11.58	7.47	8.29
10.190	2.121	360.32	321.77	323.27	3379.2	133.54	32168	0.665	10832	67.14	1.10	2.39	11.58	8.46	9.20
12.700	2.096	369.74	333.20	334.83	3357.8	139.08	31415	0.665	11603	70.24	1.10	2.94	11.58	10.09	10.71
15.215	2.070	364.24	343.83	345.59	3336.3	144.36	30752	0.665	16367	97.00	1.10	3.47	11.58	20.60	20.91
0.000	-2.070	328.40	277.65	278.71	3466.3	112.67	35492	0.664	6355	43.36	1.10	0.63	11.58	6.28	7.24
7.620	-2.146	352.26	310.17	311.55	3401.2	127.98	32976	0.665	9801	62.27	1.10	1.90	11.58	7.09	7.96
15.240	-2.096	363.13	343.92	345.67	3336.1	144.40	30747	0.665	17342	102.76	1.10	3.47	11.58	21.92	22.21
7.620	3.620	356.02	310.17	311.55	3401.2	127.98	32976	0.665	8973	57.00	1.10	1.90	11.58	6.75	7.65
7.620	-3.620	368.52	310.17	311.55	3401.2	127.98	32976	0.665	7004	44.50	1.10	1.90	11.58	6.01	7.01

Table 3 (continued)

Tube Specimen
Date: 16 February 1990
Time: 15:26:58

TA	TB	M	PA	PA-PB	Vf	Qt	Wqt
K	K	kg/h	kPa	kPa	%	W	%
285.13	566.24	9.53	3542.9	26.4	34.99	3697.0	1.14

Hot-side Temperatures:

X	Y	Tw
cm	cm	K
1.270	-0.762	406.25
2.515	-0.762	441.54
5.080	-0.381	497.16
7.620	-0.381	545.99
10.185	-0.381	590.51
12.700	-0.381	627.48
13.970	-0.381	636.07
7.595	-3.048	466.52

Insulated-Side Temperatures and Calculated Data:

											--------Uncertainties----------				
X	Y	Tw	Tf	Taw	P	V	RE	PR	h	NU	Wtw	Wtf	Wre	Wh	Wnu
cm	cm	K	K	K	kPa	m/s			W/(m²·K)		K	K	%	%	%
-0.020	0.191	346.48	291.85	291.91	3539.7	28.45	8428	0.665	0	0.00	1.10	0.77	11.58	4.90	6.08
1.288	0.191	402.96	311.92	312.00	3538.3	30.38	8061	0.665	3885	24.58	1.10	2.09	11.58	5.55	6.62
2.586	0.140	440.44	333.79	333.88	3536.9	32.49	7699	0.665	3473	20.99	1.10	2.97	11.58	5.58	6.64
3.810	0.165	468.33	355.08	355.18	3535.6	34.54	7382	0.665	3348	19.40	1.10	3.97	11.58	5.89	6.90
5.042	0.191	492.42	376.95	377.06	3534.3	36.65	7087	0.665	3343	18.60	1.10	5.06	11.58	6.40	7.35
6.350	0.203	517.92	400.54	400.67	3532.9	38.92	6799	0.666	3334	17.80	1.10	6.28	11.58	7.07	7.94
7.620	0.191	541.43	423.67	423.81	3531.6	41.15	6542	0.666	3344	17.18	1.10	7.49	11.58	7.85	8.64
8.903	0.152	563.76	447.12	447.28	3530.3	43.42	6303	0.666	3384	16.75	1.16	8.45	11.58	8.59	9.32
10.160	0.216	585.19	470.15	470.33	3528.9	45.65	6089	0.666	3444	16.47	1.25	9.47	11.58	9.45	10.11
11.430	0.191	606.37	493.57	493.76	3527.6	47.91	5887	0.666	3542	16.38	1.33	10.56	11.58	10.45	11.06
12.637	0.140	622.55	515.97	516.18	3526.3	50.08	5709	0.666	3756	16.85	1.40	11.64	11.58	11.89	12.42
13.912	0.165	631.63	539.23	539.46	3525.0	52.33	5537	0.666	4135	17.98	1.43	12.78	11.58	14.71	15.15
15.240	0.165	607.35	560.67	560.92	3523.6	54.41	5389	0.666	6425	27.20	1.34	13.81	11.58	30.61	30.82
-0.036	2.083	360.89	291.85	291.91	3539.7	28.45	8428	0.665	0	0.00	1.10	0.77	11.58	4.66	5.89
2.510	2.108	436.56	332.49	332.57	3537.0	32.36	7720	0.665	3552	21.53	1.10	2.93	11.58	5.60	6.66
5.105	2.070	492.38	378.08	378.19	3534.3	36.75	7073	0.665	3380	18.77	1.10	5.12	11.58	6.47	7.41
7.650	2.096	539.88	424.22	424.36	3531.6	41.21	6536	0.666	3405	17.48	1.10	7.51	11.58	7.97	8.74
10.190	2.121	583.56	470.70	470.88	3528.9	45.70	6084	0.666	3511	16.78	1.24	9.50	11.58	9.61	10.26
12.700	2.096	621.88	517.13	517.34	3526.3	50.19	5700	0.666	3820	17.10	1.39	11.70	11.58	12.12	12.64
15.215	2.070	610.36	560.32	560.57	3523.6	54.38	5391	0.666	6043	25.59	1.35	13.79	11.58	28.59	28.81
0.000	-2.070	381.93	291.85	291.91	3539.6	28.45	8428	0.665	3458	22.85	1.10	1.65	11.58	6.06	7.05
7.620	-2.146	545.16	423.67	423.81	3531.6	41.15	6542	0.666	3242	16.65	1.10	7.49	11.58	7.69	8.50
15.240	-2.096	607.23	560.67	560.92	3523.6	54.41	5389	0.666	6442	27.27	1.34	13.81	11.58	30.68	30.89
7.620	3.620	548.68	423.67	423.81	3531.6	41.15	6542	0.666	3150	16.18	1.10	7.49	11.58	7.55	8.37
7.620	-3.620	563.20	423.67	423.81	3531.6	41.15	6542	0.666	2822	14.50	1.16	7.49	11.58	7.06	7.93

Table 3 (continued)

Tube Specimen
Date: 9 March 1990
Time: 11:51:14

TA	TB	M	PA	PA-PB	Vf	Qt	Wqt
K	K	kg/h	kPa	kPa	%	W	%
290.12	646.68	12.83	3545.6	51.1	60.73	6225.0	1.14

Hot-side Temperatures:

X	Y	Tw
cm	cm	K
1.270	-0.762	460.10
2.515	-0.762	504.88
5.080	-0.381	569.63
7.620	-0.381	629.98
10.185	-0.381	685.40
12.700	-0.381	732.54
13.970	-0.381	743.21
7.595	-3.048	525.21

Insulated-Side Temperatures and Calculated Data:

											--------Uncertainties----------				
X	Y	Tw	Tf	Taw	P	V	RE	PR	h	NU	Wtw	Wtf	Wre	Wh	Wnu
cm	cm	K	K	K	kPa	m/s			W/(m²·K)		K	K	%	%	%
-0.020	0.191	374.13	301.33	301.46	3539.5	39.52	11107	0.665	0	0.00	1.10	0.89	11.58	4.66	5.89
1.288	0.191	452.52	326.43	326.59	3536.9	42.78	10522	0.665	4726	28.99	1.10	2.59	11.58	5.39	6.49
2.586	0.140	502.80	353.78	353.96	3534.3	46.34	9962	0.665	4187	24.33	1.10	3.71	11.58	5.38	6.48
3.810	0.165	534.63	380.40	380.61	3531.8	49.81	9481	0.665	4141	22.90	1.10	4.95	11.58	5.68	6.73
5.042	0.191	561.67	407.74	407.98	3529.3	53.37	9040	0.666	4225	22.28	1.15	6.32	11.58	6.19	7.17
6.350	0.203	591.55	437.23	437.51	3526.7	57.22	8617	0.666	4273	21.48	1.27	7.85	11.58	6.86	7.75
7.620	0.191	621.05	466.14	466.46	3524.1	61.00	8244	0.666	4285	20.61	1.39	9.37	11.58	7.60	8.41
8.903	0.152	648.85	495.46	495.82	3521.5	64.84	7904	0.666	4337	20.00	1.50	10.57	11.58	8.30	9.05
10.160	0.216	674.94	524.25	524.65	3519.0	68.62	7600	0.666	4432	19.66	1.61	11.85	11.58	9.13	9.82
11.430	0.191	703.11	553.51	553.96	3516.4	72.46	7319	0.666	4503	19.23	1.72	13.21	11.58	9.98	10.61
12.637	0.140	723.89	581.51	582.00	3514.0	76.14	7072	0.666	4742	19.57	1.80	14.56	11.58	11.26	11.82
13.912	0.165	735.20	610.59	611.13	3511.5	79.97	6836	0.666	5172	20.63	1.85	15.98	11.58	13.78	14.25
15.240	0.165	700.45	637.38	637.96	3508.8	83.52	6634	0.666	8040	31.12	1.71	17.27	11.58	28.55	28.78
-0.036	2.083	409.38	301.33	301.46	3539.5	39.51	11107	0.665	0	0.00	1.10	0.89	11.58	4.43	5.72
2.510	2.108	491.74	352.15	352.33	3534.4	46.13	9993	0.665	4462	26.01	1.10	3.65	11.58	5.46	6.54
5.105	2.070	555.24	409.15	409.39	3529.2	53.56	9019	0.666	4456	23.45	1.13	6.40	11.58	6.38	7.33
7.650	2.096	613.07	466.83	467.14	3524.1	61.09	8236	0.666	4540	21.82	1.36	9.40	11.58	7.91	8.69
10.190	2.121	668.61	524.94	525.34	3518.9	68.71	7594	0.666	4650	20.61	1.58	11.88	11.58	9.49	10.15
12.700	2.096	718.25	582.97	583.46	3513.9	76.34	7060	0.666	4989	20.55	1.78	14.63	11.58	11.81	12.35
15.215	2.070	701.67	636.94	637.53	3508.8	83.46	6637	0.666	7899	30.59	1.71	17.25	11.58	27.80	28.04
0.000	-2.070	445.58	301.33	301.46	3539.5	39.52	11107	0.665	3637	23.55	1.10	2.03	11.58	5.87	6.89
7.620	-2.146	635.00	466.14	466.46	3524.1	61.00	8244	0.666	3930	18.91	1.45	9.37	11.58	7.20	8.06
15.240	-2.096	710.20	637.38	637.96	3508.8	83.52	6634	0.666	6954	26.92	1.75	17.27	11.58	24.93	25.19
7.620	3.620	619.13	466.14	466.46	3524.1	61.00	8244	0.666	4339	20.87	1.38	9.37	11.58	7.66	8.47
7.620	-3.620	671.44	466.14	466.46	3524.1	61.00	8244	0.666	3232	15.55	1.59	9.37	11.58	6.46	7.40

Table 3 (continued)

Tube Specimen
Date: 9 March 1990
Time: 12:00:30

TA	TB	M	PA	PA-PB	Vf	Qt	Wqt
K	K	kg/h	kPa	kPa	%	W	%
287.17	542.00	18.49	3543.3	84.9	60.82	6405.0	1.16

Hot-side Temperatures:

X	Y	Tw
cm	cm	K
1.270	-0.762	415.88
2.515	-0.762	447.41
5.080	-0.381	493.28
7.620	-0.381	537.32
10.185	-0.381	576.53
12.700	-0.381	610.99
13.970	-0.381	619.32
7.595	-3.048	461.44

Insulated-Side Temperatures and Calculated Data:

											--------Uncertainties---------				
X	Y	Tw	Tf	Taw	P	V	RE	PR	h	NU	Wtw	Wtf	Wre	Wh	Wnu
cm	cm	K	K	K	kPa	m/s			W/(m²·K)		K	K	%	%	%
-0.020	0.191	349.81	294.78	295.05	3532.5	55.83	16238	0.665	0	0.00	1.10	0.73	11.58	4.87	6.06
1.288	0.191	409.26	312.69	312.99	3528.2	59.23	15608	0.665	6359	40.16	1.10	1.88	11.58	5.41	6.50
2.586	0.140	446.34	332.20	332.53	3524.0	62.93	14981	0.665	5633	34.16	1.10	2.66	11.58	5.36	6.46
3.810	0.165	467.88	351.18	351.56	3520.0	66.55	14425	0.665	5641	32.94	1.10	3.55	11.58	5.63	6.68
5.042	0.191	486.65	370.68	371.10	3516.0	70.26	13903	0.665	5782	32.55	1.10	4.52	11.58	6.09	7.08
6.350	0.203	507.88	391.72	392.18	3511.7	74.28	13388	0.666	5853	31.73	1.10	5.61	11.58	6.70	7.61
7.620	0.191	528.95	412.34	412.85	3507.6	78.23	12925	0.666	5870	30.72	1.10	6.70	11.58	7.38	8.21
8.903	0.152	548.01	433.24	433.81	3503.4	82.24	12493	0.666	5980	30.26	1.10	7.55	11.58	8.06	8.83
10.160	0.216	566.41	453.77	454.40	3499.3	86.19	12101	0.666	6118	29.99	1.17	8.46	11.58	8.85	9.56
11.430	0.191	587.19	474.64	475.32	3495.2	90.21	11731	0.666	6177	29.35	1.26	9.44	11.58	9.61	10.26
12.637	0.140	602.33	494.60	495.34	3491.3	94.07	11402	0.666	6471	29.88	1.32	10.40	11.58	10.76	11.35
13.912	0.165	610.91	515.33	516.14	3487.1	98.08	11082	0.666	6967	31.27	1.35	11.41	11.58	13.00	13.49
15.240	0.165	581.69	534.43	535.30	3482.8	101.80	10806	0.666	11141	48.76	1.23	12.34	11.58	27.54	27.77
-0.036	2.083	387.54	294.78	295.05	3532.5	55.83	16238	0.665	0	0.00	1.10	0.73	11.58	4.47	5.74
2.510	2.108	437.24	331.03	331.36	3524.2	62.71	15016	0.665	6045	36.74	1.10	2.63	11.58	5.44	6.52
5.105	2.070	480.89	371.69	372.11	3515.8	70.46	13878	0.665	6146	34.53	1.10	4.57	11.58	6.29	7.25
7.650	2.096	522.43	412.83	413.34	3507.5	78.32	12915	0.666	6247	32.67	1.10	6.72	11.58	7.69	8.50
10.190	2.121	561.95	454.27	454.89	3499.2	86.28	12092	0.666	6403	31.36	1.15	8.49	11.58	9.17	9.85
12.700	2.096	597.73	495.64	496.39	3491.1	94.27	11385	0.666	6827	31.48	1.30	10.45	11.58	11.31	11.87
15.215	2.070	582.98	534.12	534.99	3482.9	101.74	10810	0.666	10863	47.56	1.24	12.32	11.58	26.62	26.87
0.000	-2.070	422.40	294.78	295.05	3532.4	55.83	16238	0.665	4234	27.80	1.10	1.49	11.58	5.84	6.86
7.620	-2.146	540.05	412.34	412.85	3507.6	78.23	12925	0.666	5357	28.04	1.10	6.70	11.58	6.98	7.86
15.240	-2.096	590.91	534.43	535.30	3482.8	101.80	10806	0.666	9293	40.67	1.27	12.34	11.58	23.26	23.54
7.620	3.620	529.05	412.34	412.85	3507.6	78.23	12925	0.666	5865	30.70	1.10	6.70	11.58	7.37	8.21
7.620	-3.620	577.12	412.34	412.85	3507.6	78.23	12925	0.666	4149	21.71	1.22	6.70	11.58	6.12	7.10

Table 3 (continued)

Tube Specimen
Date: 9 March 1990
Time: 12:06:58

TA	TB	M	PA	PA-PB	Vf	Qt	Wqt
K	K	kg/h	kPa	kPa	%	W	%
284.41	453.07	28.60	3538.9	159.6	60.87	6552.0	1.21

Hot-side Temperatures:

X	Y	Tw
cm	cm	K
1.270	-0.762	377.21
2.515	-0.762	398.27
5.080	-0.381	428.65
7.620	-0.381	459.11
10.185	-0.381	484.92
12.700	-0.381	507.40
13.970	-0.381	512.92
7.595	-3.048	408.72

Insulated-Side Temperatures and Calculated Data:

											---------Uncertainties----------				
X	Y	Tw	Tf	Taw	P	V	RE	PR	h	NU	Wtw	Wtf	Wre	Wh	Wnu
cm	cm	K	K	K	kPa	m/s			W/(m²·K)		K	K	%	%	%
-0.020	0.191	328.86	288.84	289.45	3517.0	85.03	25463	0.664	0	0.00	1.10	0.61	11.58	5.30	6.41
1.288	0.191	371.55	300.65	301.31	3509.4	88.63	24797	0.665	8918	57.83	1.10	1.29	11.58	5.49	6.56
2.586	0.140	398.31	313.51	314.23	3501.8	92.55	24105	0.665	7801	49.18	1.10	1.79	11.58	5.35	6.45
3.810	0.165	411.29	326.03	326.81	3494.6	96.38	23475	0.665	7947	48.80	1.10	2.37	11.58	5.58	6.64
5.042	0.191	423.36	338.88	339.73	3487.4	100.32	22867	0.665	8173	48.90	1.10	3.01	11.58	5.97	6.98
6.350	0.203	437.55	352.75	353.67	3479.8	104.58	22252	0.665	8259	48.09	1.10	3.72	11.58	6.48	7.41
7.620	0.191	451.73	366.34	367.33	3472.4	108.78	21685	0.665	8261	46.88	1.10	4.44	11.58	7.05	7.92
8.903	0.152	463.91	380.12	381.19	3464.8	113.06	21145	0.666	8446	46.74	1.10	5.00	11.58	7.66	8.47
10.160	0.216	475.92	393.64	394.80	3457.5	117.27	20645	0.666	8644	46.71	1.10	5.60	11.58	8.35	9.10
11.430	0.191	490.30	407.39	408.63	3450.1	121.57	20165	0.666	8657	45.69	1.10	6.25	11.58	8.96	9.66
12.637	0.140	499.85	420.54	421.87	3443.0	125.70	19730	0.666	9082	46.90	1.10	6.89	11.58	9.99	10.63
13.912	0.165	505.64	434.19	435.61	3435.6	130.01	19301	0.666	9645	48.73	1.10	7.56	11.58	11.87	12.41
15.240	0.165	483.70	446.77	448.28	3427.8	134.02	18925	0.666	14930	73.97	1.10	8.17	11.58	24.19	24.46
-0.036	2.083	367.85	288.84	289.45	3517.1	85.03	25463	0.664	0	0.00	1.10	0.61	11.58	4.53	5.79
2.510	2.108	390.48	312.74	313.46	3502.2	92.32	24145	0.665	8500	53.68	1.10	1.76	11.58	5.45	6.54
5.105	2.070	418.14	339.55	340.40	3487.1	100.52	22836	0.665	8798	52.57	1.10	3.04	11.58	6.19	7.16
7.650	2.096	446.37	366.66	367.66	3472.2	108.88	21672	0.665	8858	50.24	1.10	4.45	11.58	7.37	8.20
10.190	2.121	472.98	393.97	395.13	3457.3	117.37	20634	0.666	9007	48.65	1.10	5.62	11.58	8.62	9.34
12.700	2.096	496.69	421.22	422.56	3442.6	125.91	19708	0.666	9548	49.25	1.10	6.92	11.58	10.45	11.06
15.215	2.070	484.52	446.57	448.08	3427.9	133.96	18931	0.666	14636	72.53	1.10	8.16	11.58	23.52	23.79
0.000	-2.070	398.88	288.84	289.45	3516.9	85.03	25463	0.664	5041	33.54	1.10	1.05	11.58	5.83	6.85
7.620	-2.146	460.17	366.34	367.33	3472.4	108.78	21685	0.665	7510	42.62	1.10	4.44	11.58	6.68	7.59
15.240	-2.096	490.89	446.77	448.28	3427.8	134.02	18925	0.666	12408	61.47	1.10	8.17	11.58	20.44	20.76
7.620	3.620	452.83	366.34	367.33	3472.4	108.78	21685	0.665	8154	46.27	1.10	4.44	11.58	7.00	7.87
7.620	-3.620	495.00	366.34	367.33	3472.4	108.78	21685	0.665	5461	30.99	1.10	4.44	11.58	5.76	6.80

Table 3 (continued)

Tube Specimen
Date: 9 March 1990
Time: 12:13:23

TA	TB	M	PA	PA-PB	Vf	Qt	Wqt
K	K	kg/h	kPa	kPa	%	W	%
282.80	406.89	38.32	3540.3	261.1	60.88	6443.0	1.28

Hot-side Temperatures:

X	Y	Tw
cm	cm	K
1.270	-0.762	356.43
2.515	-0.762	372.11
5.080	-0.381	395.05
7.620	-0.381	418.44
10.185	-0.381	437.42
12.700	-0.381	453.84
13.970	-0.381	458.21
7.595	-3.048	382.67

Insulated-Side Temperatures and Calculated Data:

											---------Uncertainties----------				
X	Y	Tw	Tf	Taw	P	V	RE	PR	h	NU	Wtw	Wtf	Wre	Wh	Wnu
cm	cm	K	K	K	kPa	m/s			W/(m²·K)		K	K	%	%	%
-0.020	0.191	317.27	285.41	286.48	3503.2	113.04	34390	0.664	0	0.00	1.10	0.56	11.58	5.83	6.86
1.288	0.191	351.25	294.04	295.19	3490.8	116.81	33721	0.665	10986	72.27	1.10	1.00	11.58	5.61	6.67
2.586	0.140	372.36	303.44	304.67	3478.6	120.89	33022	0.665	9527	61.41	1.10	1.35	11.58	5.40	6.49
3.810	0.165	381.51	312.58	313.90	3467.0	124.88	32366	0.665	9764	61.69	1.10	1.76	11.58	5.58	6.65
5.042	0.191	390.20	321.98	323.38	3455.4	128.99	31725	0.665	10057	62.30	1.10	2.22	11.58	5.91	6.92
6.350	0.203	401.06	332.10	333.60	3443.0	133.45	31066	0.665	10099	61.26	1.10	2.74	11.58	6.32	7.28
7.620	0.191	411.55	342.03	343.63	3431.0	137.85	30451	0.665	10093	60.02	1.10	3.26	11.58	6.80	7.70
8.903	0.152	420.40	352.09	353.79	3418.9	142.34	29856	0.665	10313	60.13	1.10	3.68	11.58	7.33	8.17
10.160	0.216	429.24	361.96	363.78	3407.0	146.78	29299	0.666	10532	60.27	1.10	4.12	11.58	7.93	8.71
11.430	0.191	440.41	372.00	373.92	3395.1	151.31	28757	0.666	10456	58.73	1.10	4.59	11.58	8.40	9.14
12.637	0.140	447.31	381.59	383.63	3383.7	155.68	28261	0.666	10937	60.38	1.10	5.06	11.58	9.29	9.96
13.912	0.165	451.63	391.56	393.72	3371.6	160.25	27767	0.666	11468	62.21	1.10	5.55	11.58	10.85	11.44
15.240	0.165	433.74	400.73	403.01	3359.1	164.56	27330	0.666	16917	90.32	1.10	6.00	11.58	20.94	21.25
-0.036	2.083	352.18	285.41	286.48	3503.3	113.04	34390	0.664	0	0.00	1.10	0.56	11.58	4.63	5.87
2.510	2.108	365.94	302.88	304.10	3479.3	120.64	33063	0.665	10411	67.19	1.10	1.33	11.58	5.51	6.59
5.105	2.070	386.06	322.46	323.86	3454.8	129.21	31692	0.665	10814	66.92	1.10	2.24	11.58	6.11	7.09
7.650	2.096	407.35	342.26	343.86	3430.7	137.96	30436	0.665	10799	64.19	1.10	3.27	11.58	7.08	7.95
10.190	2.121	427.51	362.20	364.02	3406.8	146.88	29286	0.666	10860	62.12	1.10	4.13	11.58	8.11	8.87
12.700	2.096	445.42	382.09	384.14	3383.1	155.90	28236	0.666	11356	62.63	1.10	5.09	11.58	9.60	10.26
15.215	2.070	434.83	400.58	402.86	3359.3	164.49	27337	0.666	16402	87.59	1.10	6.00	11.58	20.16	20.48
0.000	-2.070	385.95	285.41	286.48	3503.0	113.05	34390	0.664	5454	36.56	1.10	0.85	11.58	5.85	6.87
7.620	-2.146	418.73	342.03	343.63	3431.0	137.85	30451	0.665	9128	54.28	1.10	3.26	11.58	6.45	7.39
15.240	-2.096	439.16	400.73	403.01	3359.1	164.56	27330	0.666	14381	76.78	1.10	6.00	11.58	18.14	18.49
7.620	3.620	413.64	342.03	343.63	3431.0	137.85	30451	0.665	9791	58.22	1.10	3.26	11.58	6.69	7.60
7.620	-3.620	452.55	342.03	343.63	3431.0	137.85	30451	0.665	6294	37.43	1.10	3.26	11.58	5.53	6.60

Table 3 (continued)

Tube Specimen
Date: 9 March 1990
Time: 12:24:05

TA	TB	M	PA	PA-PB	Vf	Qt	Wqt
K	K	kg/h	kPa	kPa	%	W	%
288.28	589.06	15.56	3569.7	67.0	60.86	6369.0	1.15

Hot-side Temperatures:

X	Y	Tw
cm	cm	K
1.270	-0.762	435.29
2.515	-0.762	473.38
5.080	-0.381	527.92
7.620	-0.381	579.27
10.185	-0.381	626.12
12.700	-0.381	666.97
13.970	-0.381	676.82
7.595	-3.048	518.73

Insulated-Side Temperatures and Calculated Data:

											Uncertainties				
X	Y	Tw	Tf	Taw	P	V	RE	PR	h	NU	Wtw	Wtf	Wre	Wh	Wnu
cm	cm	K	K	K	kPa	m/s			W/(m²·K)		K	K	%	%	%
-0.020	0.191	359.17	297.46	297.65	3561.4	47.04	13589	0.665	0	0.00	1.10	0.80	11.58	4.77	5.98
1.288	0.191	428.28	318.63	318.84	3558.0	50.38	12974	0.665	5563	34.69	1.10	2.20	11.58	5.40	6.49
2.586	0.140	471.89	341.68	341.93	3554.6	54.01	12373	0.665	4906	29.18	1.10	3.13	11.58	5.37	6.46
3.810	0.165	498.25	364.12	364.40	3551.4	57.55	11849	0.665	4876	27.78	1.10	4.18	11.58	5.65	6.70
5.042	0.191	520.67	387.17	387.48	3548.2	61.20	11362	0.665	4988	27.26	1.10	5.34	11.58	6.13	7.11
6.350	0.203	546.02	412.03	412.39	3544.8	65.13	10888	0.666	5039	26.39	1.10	6.62	11.58	6.76	7.66
7.620	0.191	570.54	436.40	436.80	3541.5	69.00	10466	0.666	5067	25.51	1.19	7.91	11.58	7.48	8.31
8.903	0.152	593.50	461.12	461.57	3538.1	72.93	10076	0.666	5147	24.95	1.28	8.92	11.58	8.18	8.94
10.160	0.216	615.46	485.38	485.88	3534.8	76.79	9725	0.666	5260	24.60	1.37	9.99	11.58	8.98	9.68
11.430	0.191	640.09	510.05	510.60	3531.5	80.72	9397	0.666	5307	23.99	1.47	11.15	11.58	9.76	10.40
12.637	0.140	658.12	533.65	534.24	3528.4	84.49	9107	0.666	5557	24.35	1.54	12.28	11.58	10.94	11.52
13.912	0.165	668.29	558.15	558.81	3525.0	88.42	8827	0.666	5997	25.46	1.58	13.48	11.58	13.25	13.73
15.240	0.165	636.92	580.73	581.45	3521.6	92.05	8587	0.666	9264	38.27	1.46	14.57	11.58	27.21	27.45
-0.036	2.083	395.78	297.46	297.65	3561.5	47.04	13589	0.665	0	0.00	1.10	0.80	11.58	4.46	5.73
2.510	2.108	462.07	340.31	340.55	3554.8	53.79	12407	0.665	5237	31.24	1.10	3.09	11.58	5.44	6.53
5.105	2.070	514.60	388.36	388.68	3548.1	61.38	11338	0.666	5280	28.79	1.10	5.40	11.58	6.32	7.28
7.650	2.096	563.48	436.98	437.38	3541.4	69.09	10456	0.666	5375	27.03	1.16	7.93	11.58	7.79	8.58
10.190	2.121	609.86	485.96	486.46	3534.8	76.88	9717	0.666	5524	25.82	1.35	10.02	11.58	9.34	10.01
12.700	2.096	652.68	534.88	535.48	3528.2	84.69	9092	0.666	5870	25.68	1.52	12.34	11.58	11.51	12.06
15.215	2.070	637.94	580.37	581.08	3521.6	91.99	8591	0.666	9117	37.68	1.46	14.55	11.58	26.54	26.78
0.000	-2.070	429.40	297.46	297.65	3561.4	47.04	13589	0.665	4070	26.57	1.10	1.73	11.58	5.86	6.88
7.620	-2.146	583.15	436.40	436.80	3541.5	69.00	10466	0.666	4631	23.31	1.24	7.91	11.58	7.08	7.95
15.240	-2.096	646.52	580.73	581.45	3521.6	92.05	8587	0.666	7897	32.62	1.49	14.57	11.58	23.46	23.73
7.620	3.620	570.09	436.40	436.80	3541.5	69.00	10466	0.666	5085	25.60	1.19	7.91	11.58	7.50	8.32
7.620	-3.620	618.70	436.40	436.80	3541.5	69.00	10466	0.666	3726	18.76	1.38	7.91	11.58	6.30	7.26

Table 4. Uncertainties in data analysis parameters
and calculated quantities

Uncertainty Parameter	Major Source of Uncertainty	Magnitude of Uncertainty	Estimated or Calculated
Tube Inner Diameter, W_{dh}	Measurement	2%	Estimated
Length of Heated Zone, W_L	Measurement	1 mm	Estimated
Location of Temperature Probe, W_{loc}	Measurement	1 mm	Estimated
Tube-to-Tube Flow Uniformity, W_{fu}	Manifold Uniformity	5%	Estimated
Pressure Loss Coefficient, W_K	Flow Geometry	0.2	Estimated
Fluid Temperature, W_{tf}	Flow Uniformity	0.5-17.3 K	Calculated
Total Heat Flow, W_{qt}	Inlet and outlet Temperature	1.1-2.4%	Calculated
Fluid Velocity, W_v	Flow Uniformity	5.5-6.0%	Calculated
Friction Factor, W_f	Entrance and Exit Losses	12-14% for Re>3000; 37% at Re=2200	Calculated
Heat Transfer Coefficient, W_h	Flow Uniformity	6-13% for 0.2<x/L<0.8	Calculated
Reynolds Number, W_{re}	Viscosity Function, Flow Uniformity	12%	Calculated
Nusselt Number, W_{nu}	Flow Uniformity	6-13% for 0.2<x/L<0.8	Calculated
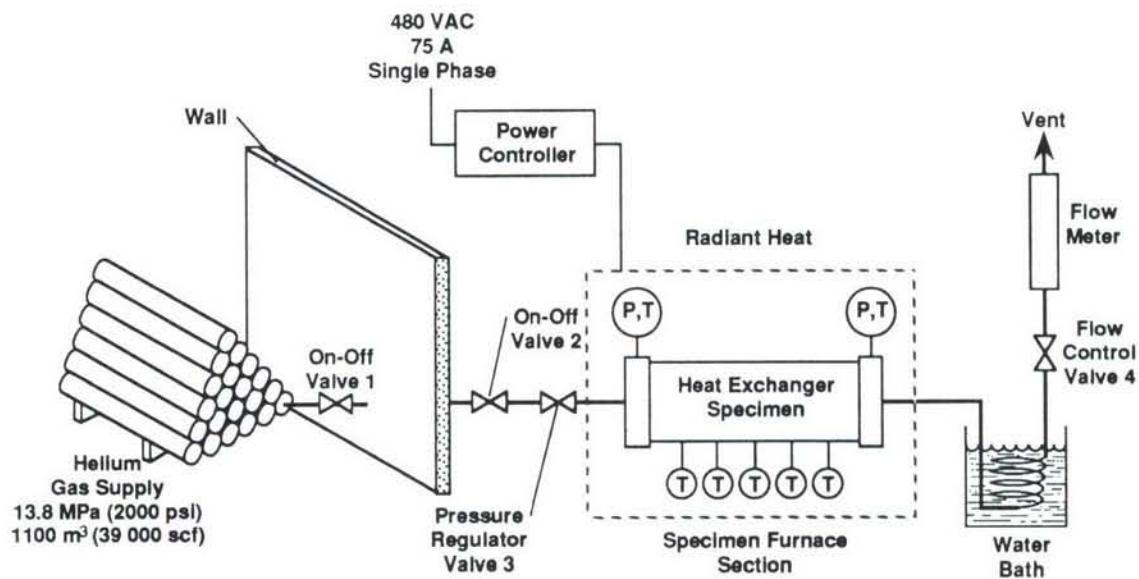
Figure 1. Helium flow loop.
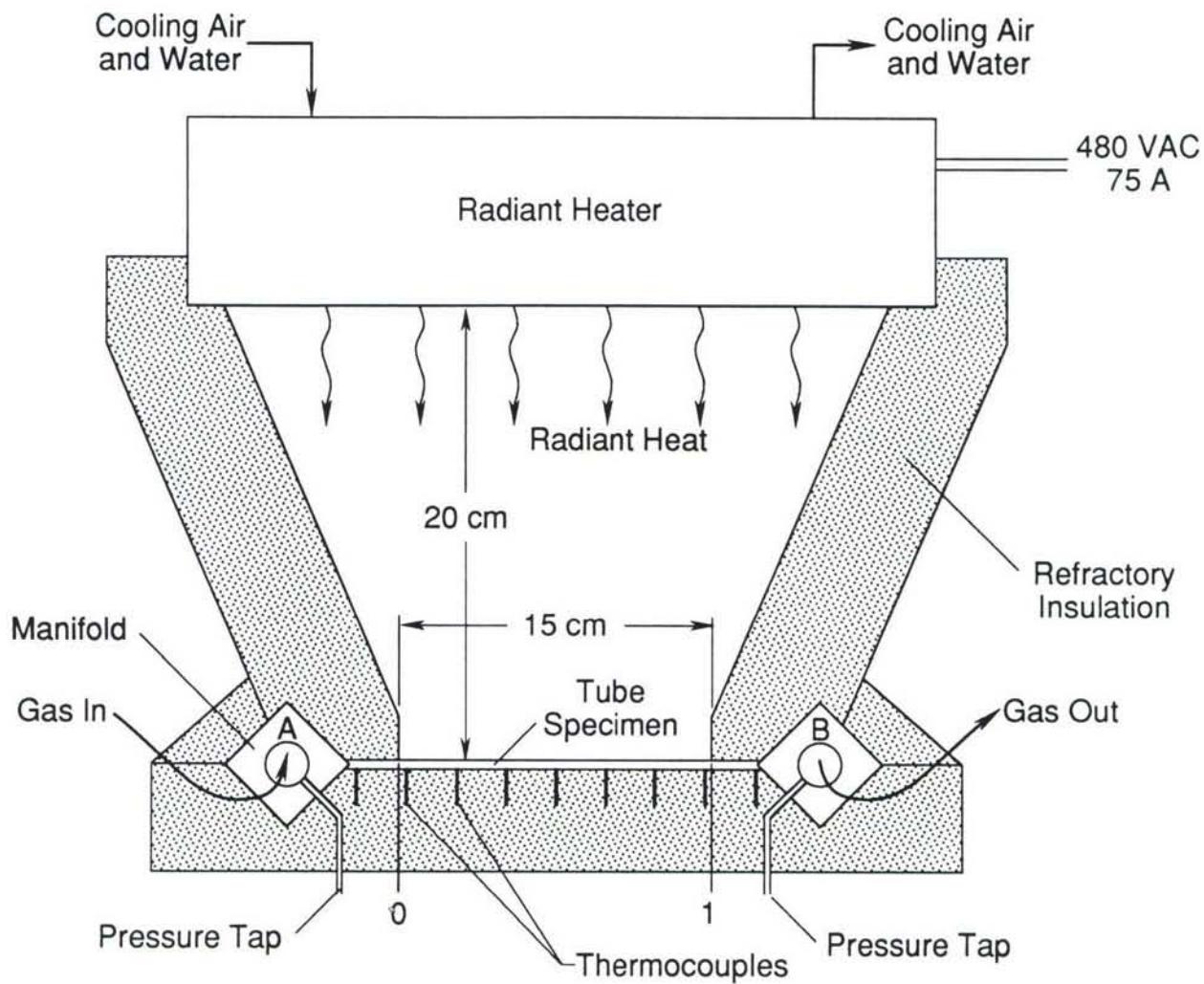
Figure 2. Specimen furnace, showing location of inlet gas temperature and upstream pressure (A), and outlet gas temperature and downstream pressure (B).
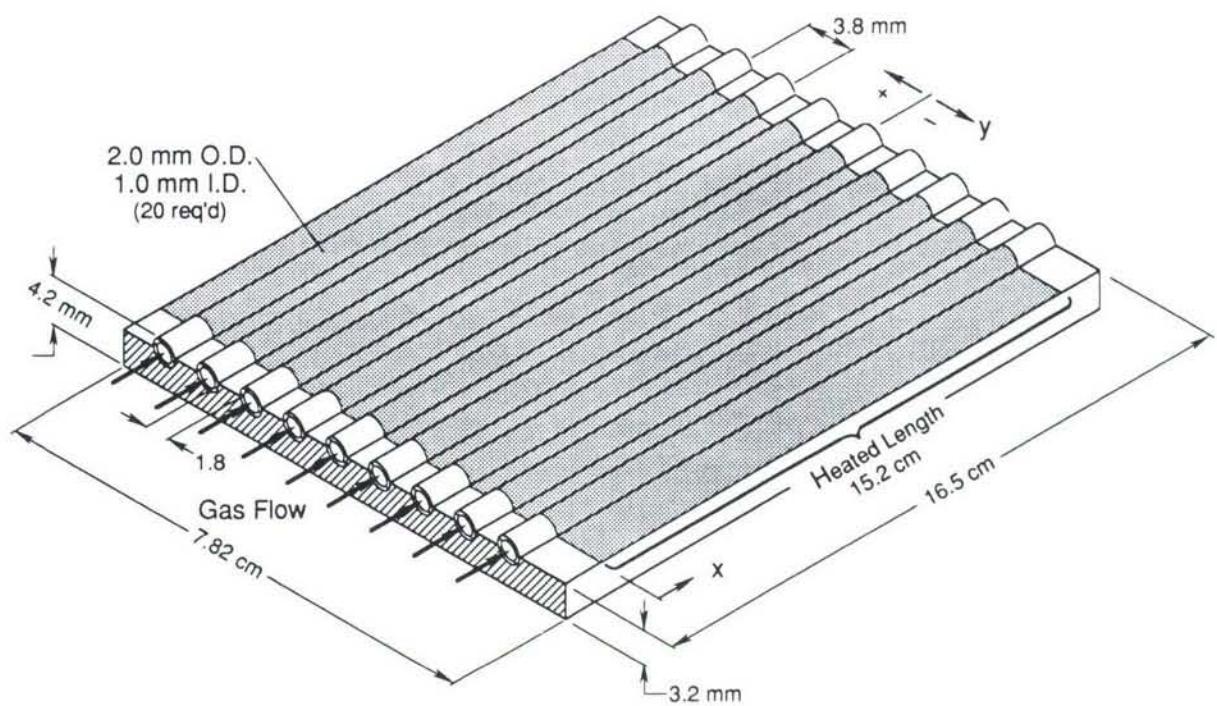
Figure 3.   Tube specimen.

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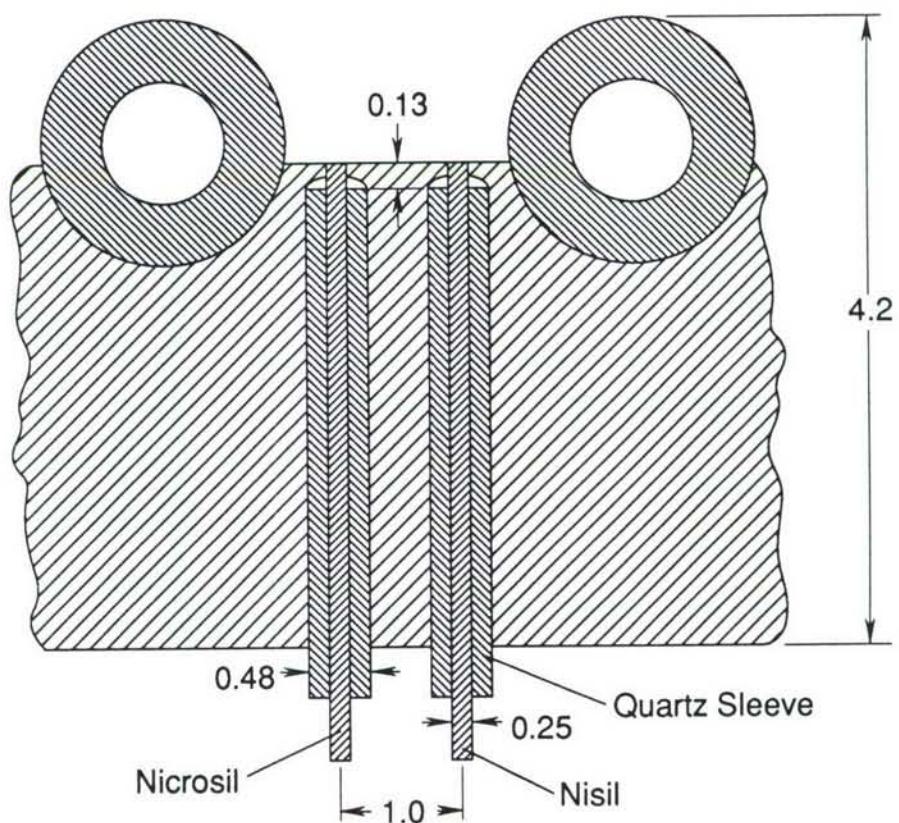
Figure 4. Technique for mounting thermocouples on tube specimen.
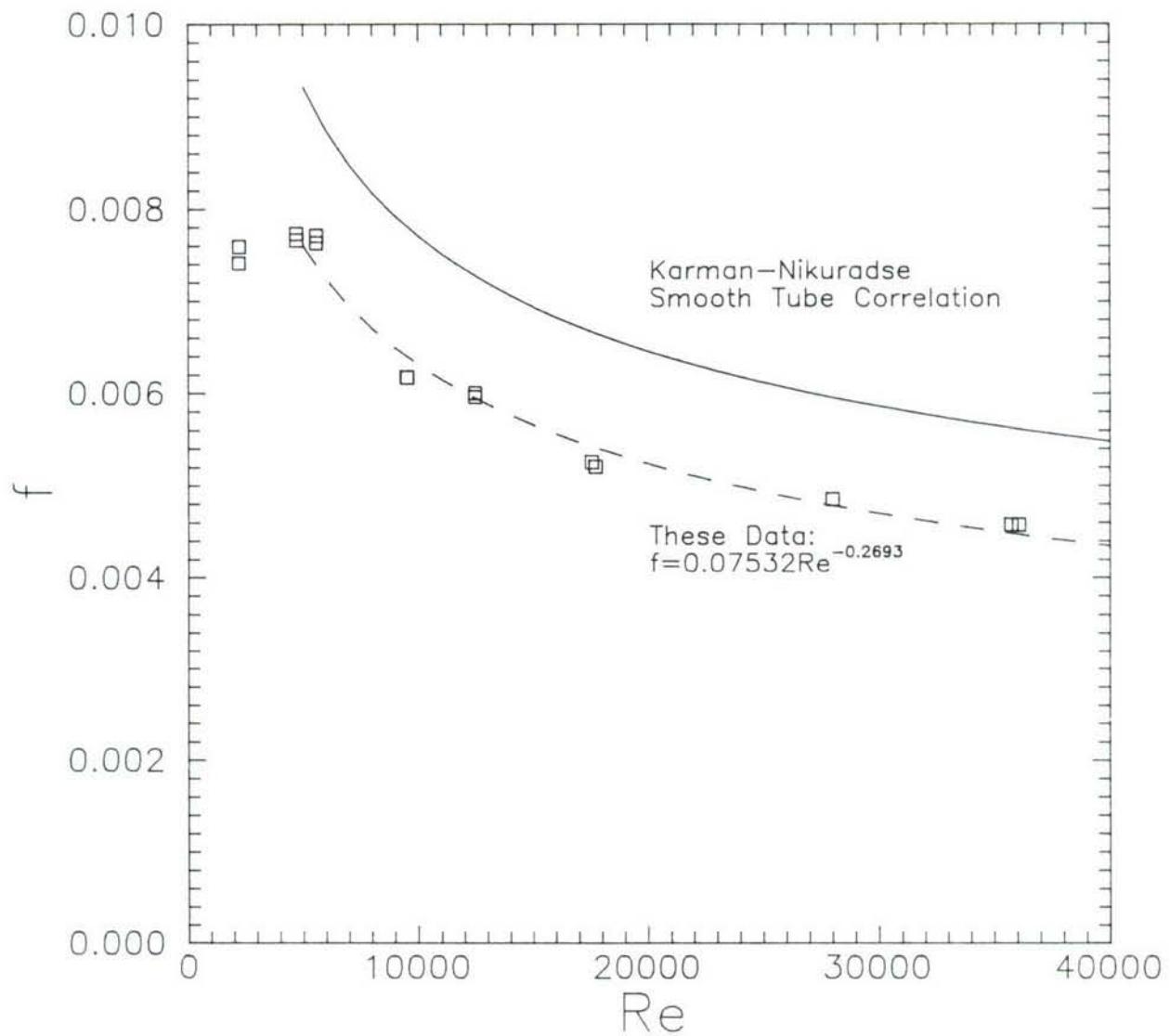
Figure 5.   Friction factor (f) as a function of Reynolds number (Re) for experiment 1, no heating.
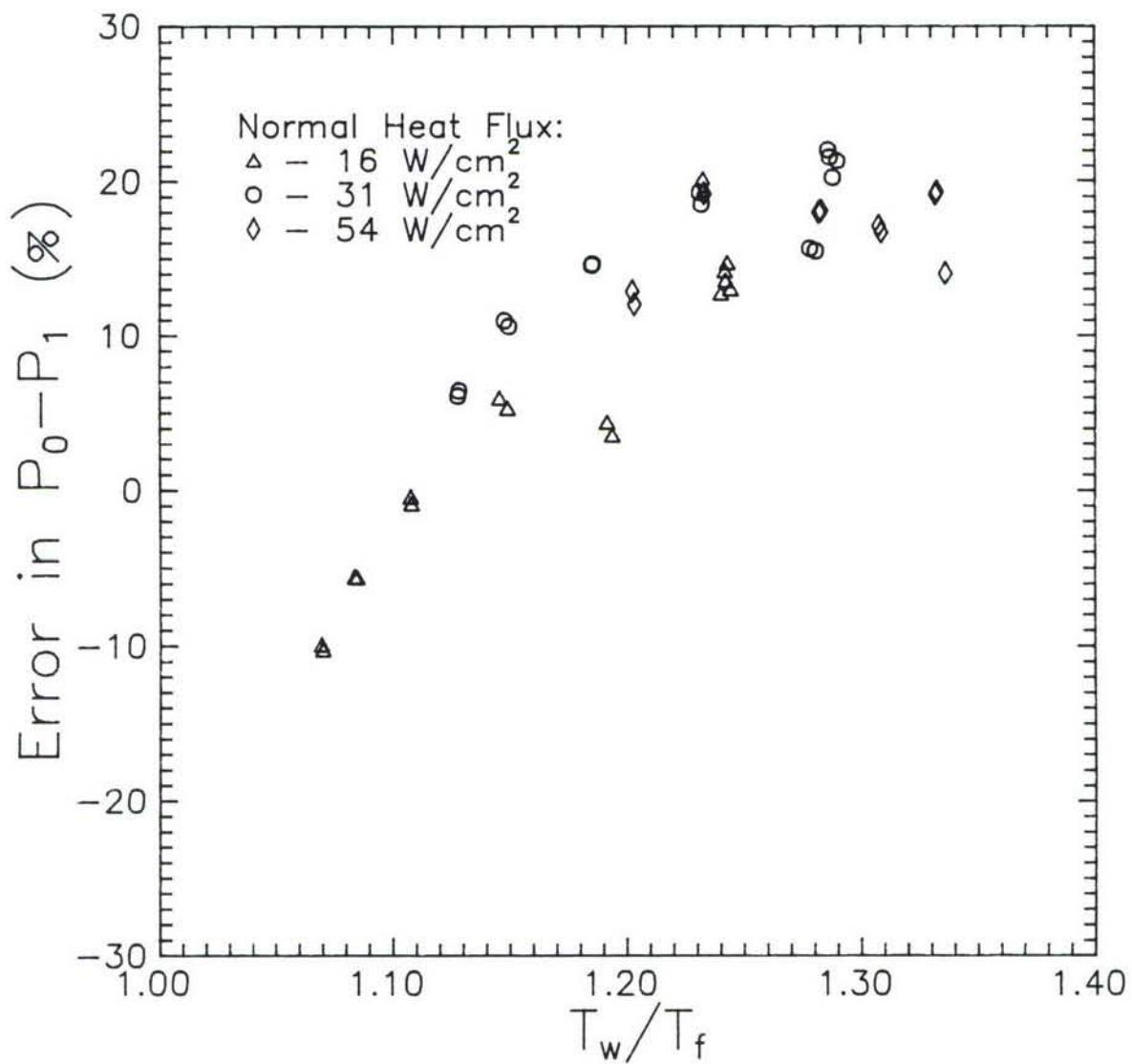
Figure 6. Percent difference between predicted and measured pressure drop (P_0-P_1) as a function of wall-to-gas temperature ratio (T_w/T_f) for heat transfer experiments.
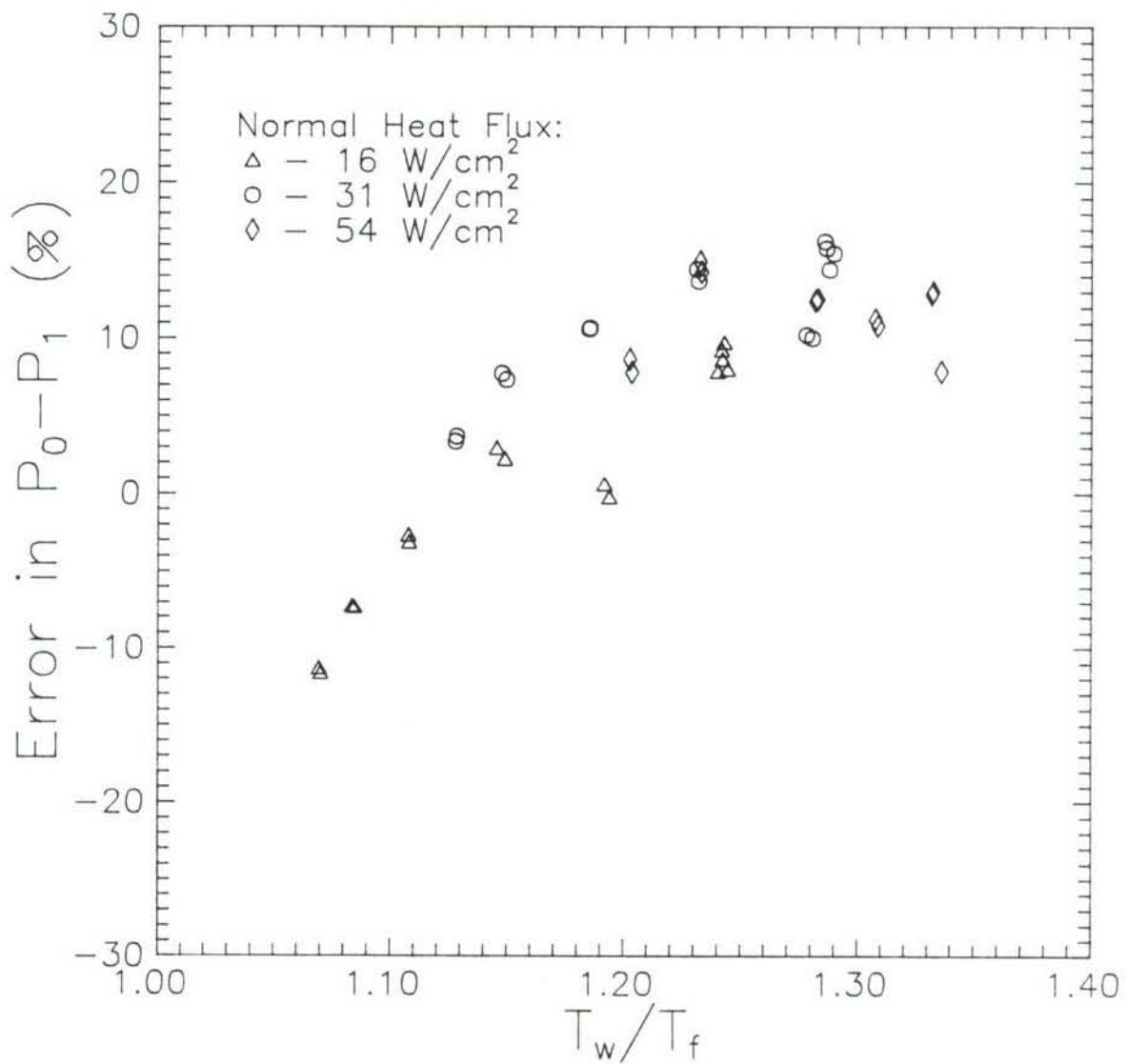
Figure 7. Percent difference between predicted and measured pressure drop (P_0-P_1) as a function of wall-to-gas temperature ratio (T_w/T_f) for heat transfer experiments, using method of Rohsenow and Choi to account for variable property effects.
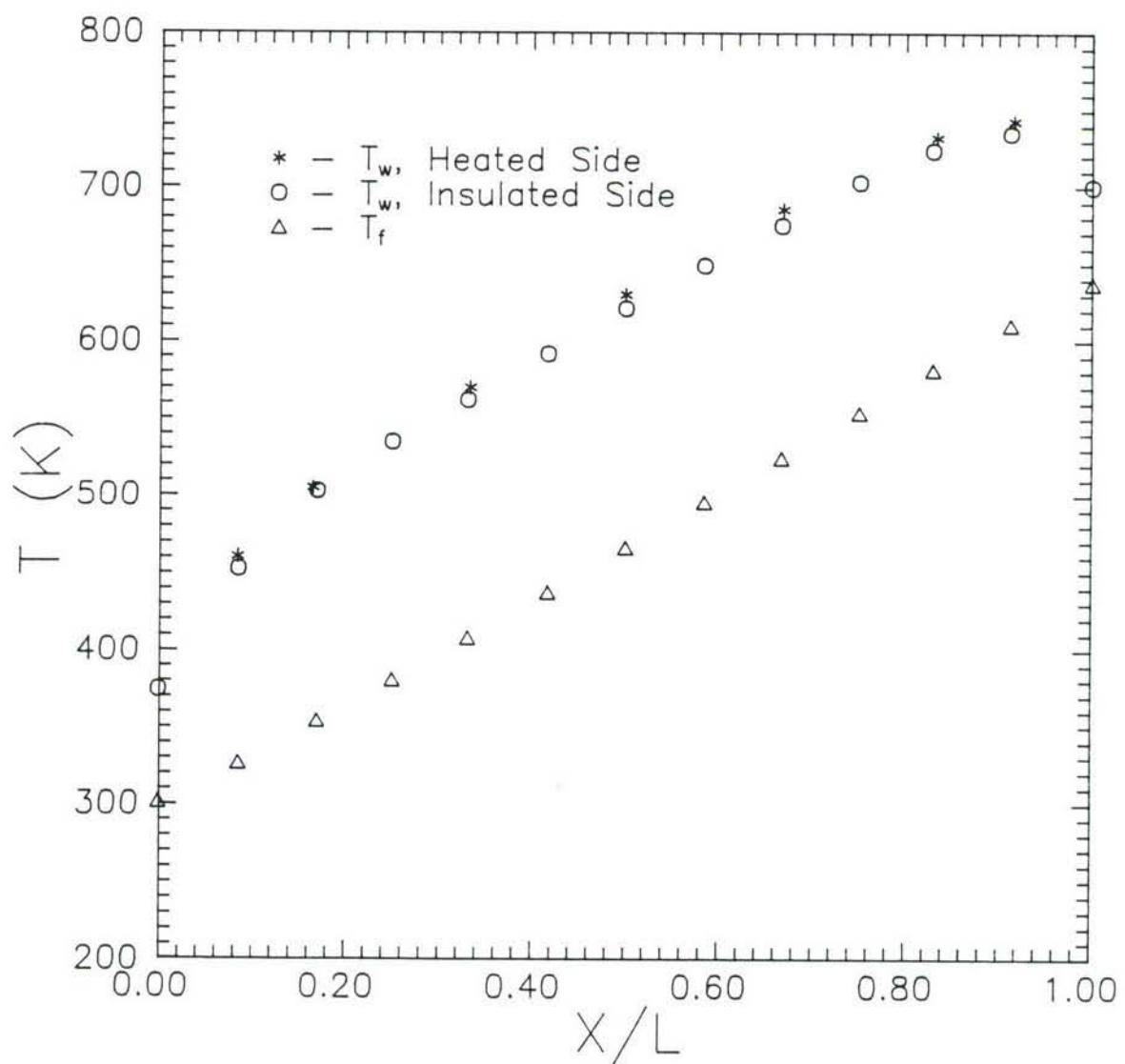
Figure 8. Wall (T_w) and gas (T_f) temperatures as a function of x/L; experiment 5, 12.8 kg/h helium flow, and y/W = 0.
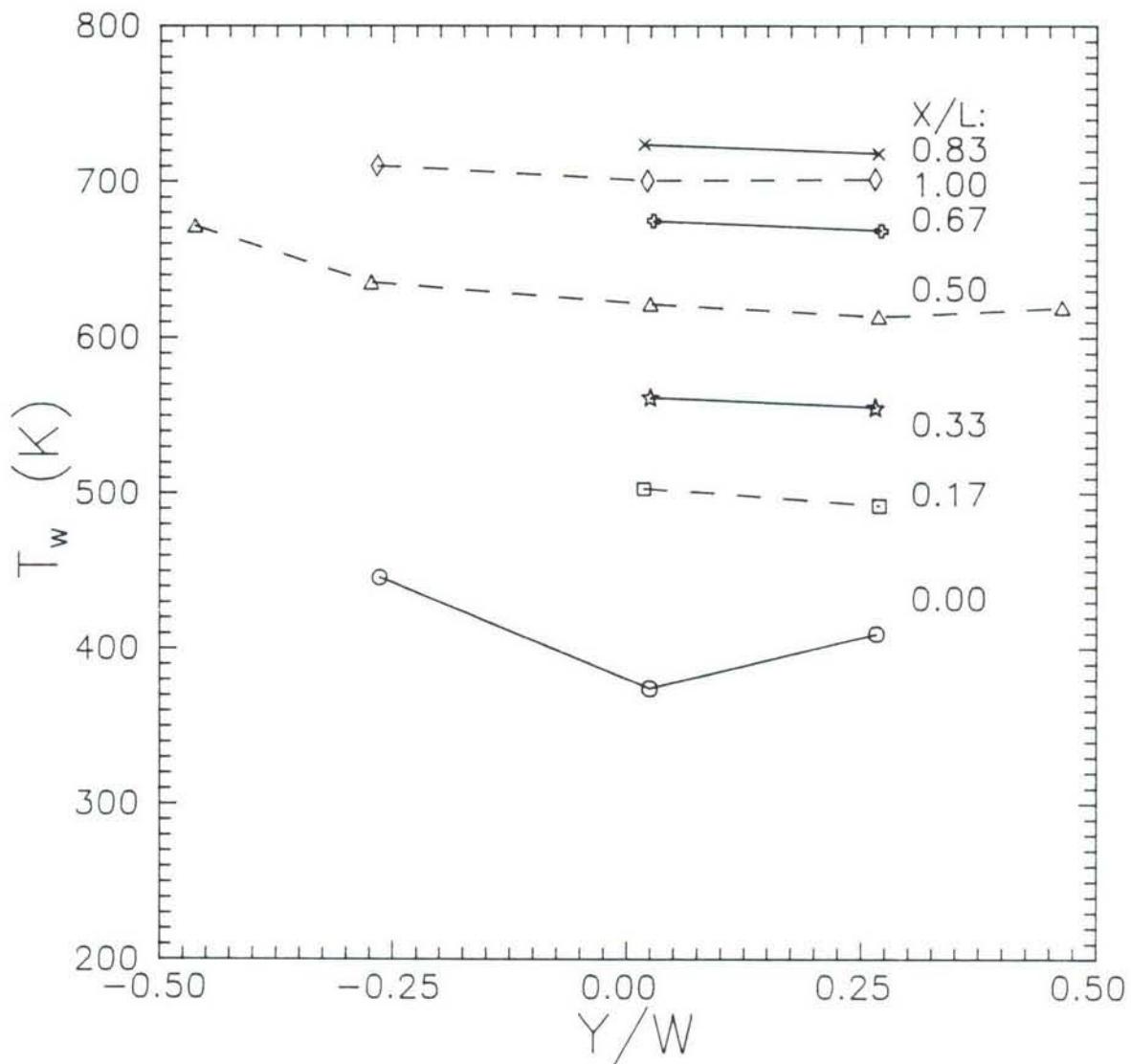
Figure 9. Wall temperature (T_w) as a function of y/W at several x/L locations; experiment 5, 12.8 kg/h helium flow.
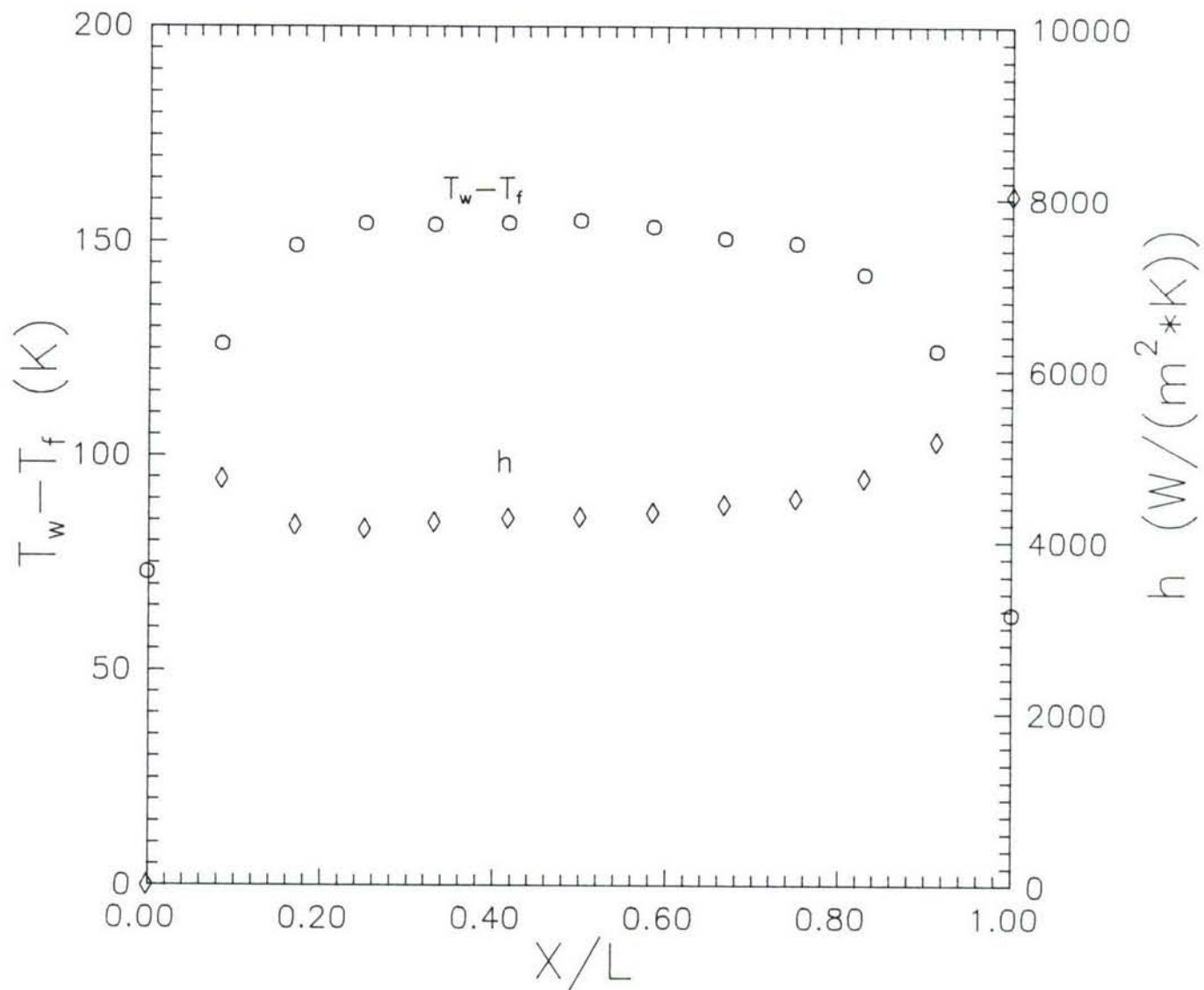
Figure 10. Wall-to-gas temperature difference (T_w-T_f) and heat transfer coefficient (h) as a function of x/L; experiment 5, 12.8 kg/h helium flow and y/W = 0.
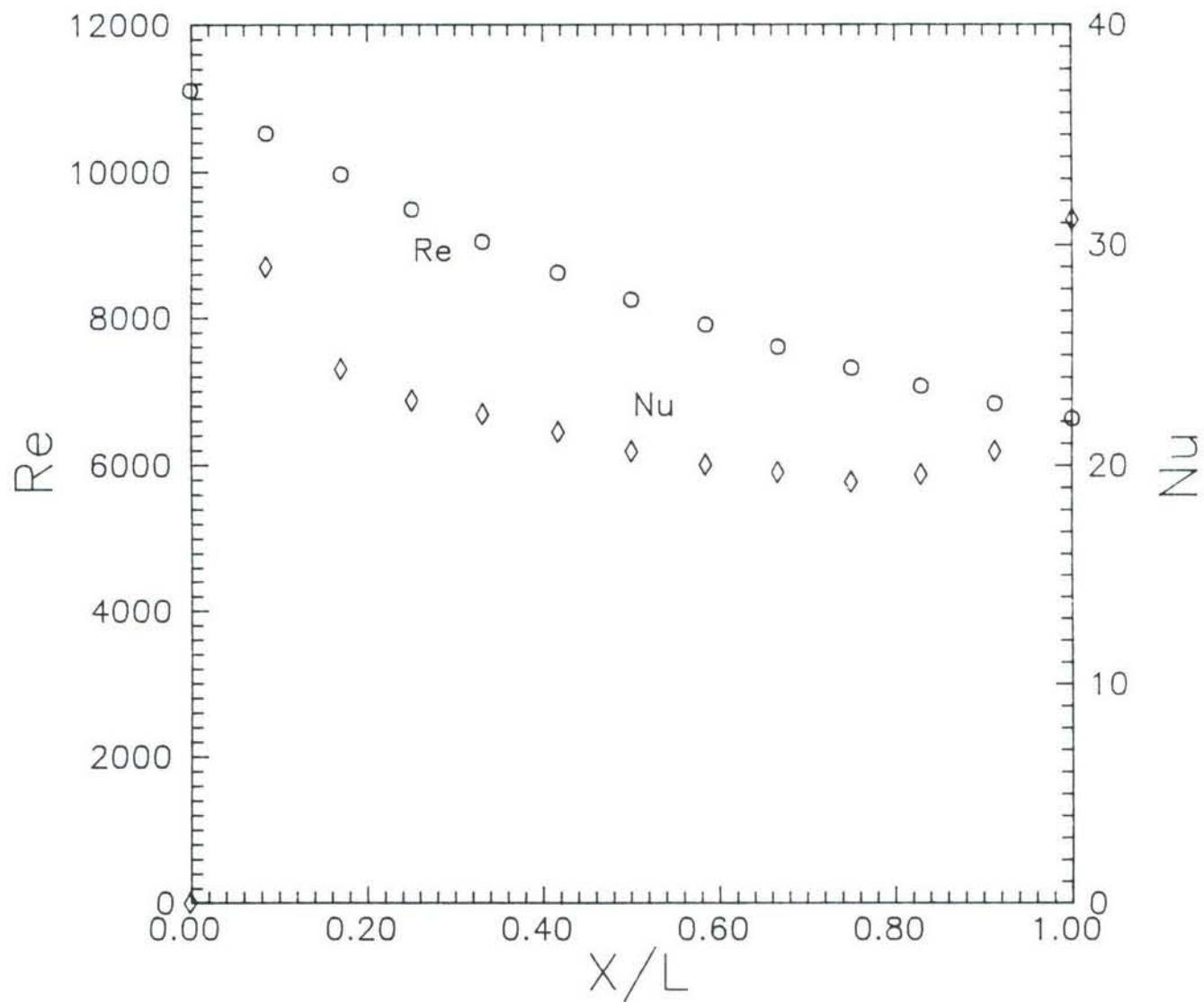
Figure 11. Reynolds number (Re) and Nusselt number (Nu) as a function of x/L; experiment 5, 12.8 kg/h helium flow and y/W = 0.
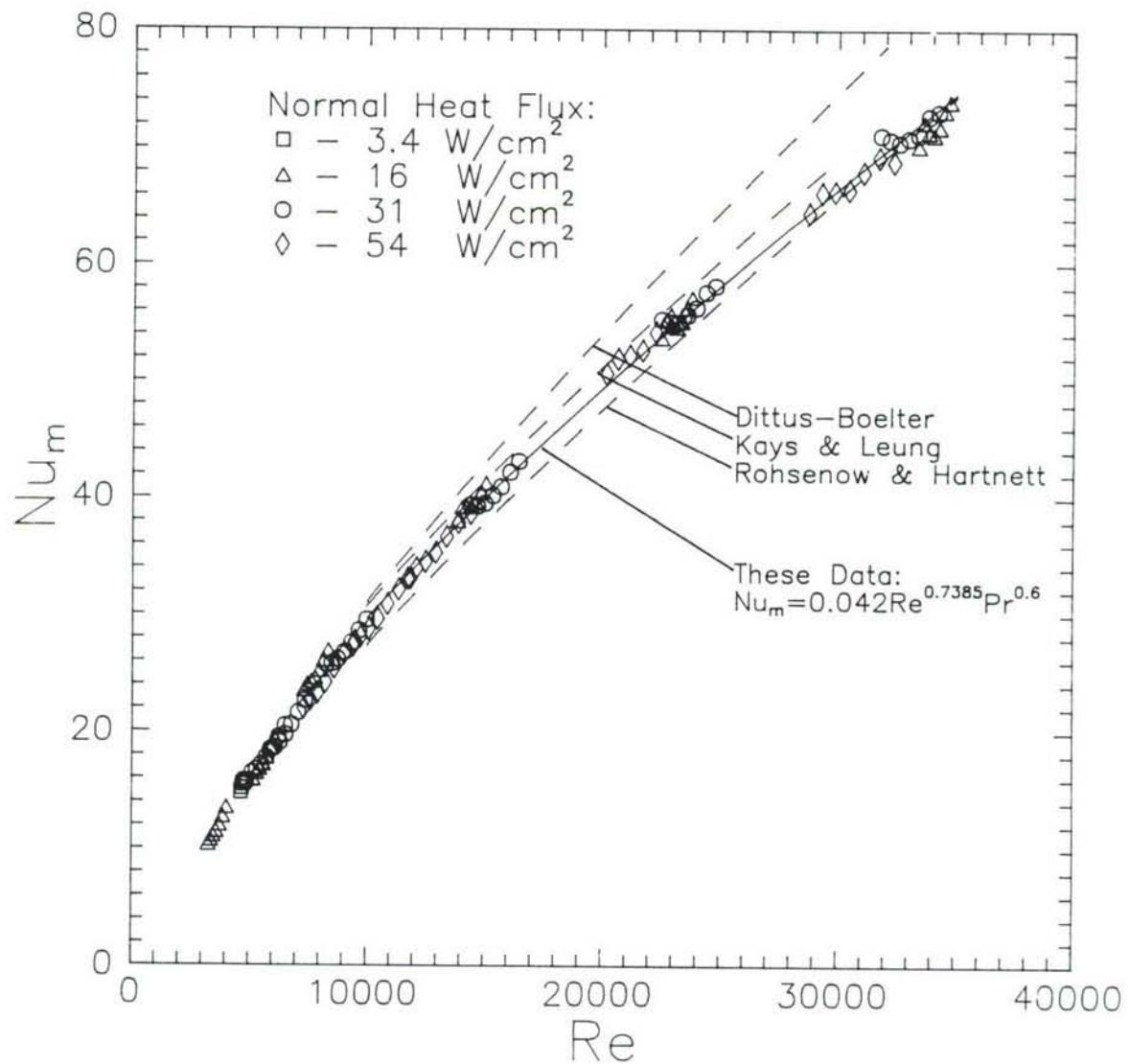
Figure 12. Modified Nusselt number (Nu_m) as a function of Reynolds number (Re); all heated experiments with $0.2 < x/L < 0.8$ and $y/W = 0$.

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5. AUTHOR(S)

Douglas A. Olson & Michael P. Glover

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11. ABSTRACT (A 200-WORD OR LESS FACTUAL SUMMARY OF MOST SIGNIFICANT INFORMATION. IF DOCUMENT INCLUDES A SIGNIFICANT BIBLIOGRAPHY OR LITERATURE SURVEY, MENTION IT HERE.)

We have constructed a compact heat exchanger consisting of circular tubes in parallel brazed to a grooved base plate. This tube specimen heat exchanger was tested in an apparatus which radiatively heated the specimen on one side at a heat flux of up to 54 W/cm^2, and cooled the specimen with helium gas at 3.5 MPa and Reynolds numbers of 3000 to 35 000. The measured friction factor of the tube specimen was lower than that of a circular tube with fully developed turbulent flow, although our uncertainty was high due to entrance and exit losses. The measured Nusselt number, when modified to account for differences in fluid properties between the wall and the cooling fluid, agreed with past correlations for fully developed turbulent flow in circular tubes.

12. KEY WORDS (6 TO 12 ENTRIES; ALPHABETICAL ORDER; CAPITALIZE ONLY PROPER NAMES; AND SEPARATE KEY WORDS BY SEMICOLONS)

apparatus; compact heat exchanger; circular tube; convection heat transfer; friction factor; high temperature; National Aerospace Plane; radiative furnace; turbulent flow; variable property effects.

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